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Volume 6 2020

Including articles from the AGM 2019 Geoff Brown Memorial Lecture, the 'From the bottom of the ocean to the depths of space' Symposium 2019 lectures (at The Open University), OUGS Members' field trip reports, the Annual Report for 2019, and the 2019 Moyra Eldridge Photographic Competition Winning and Highly Commended photographs

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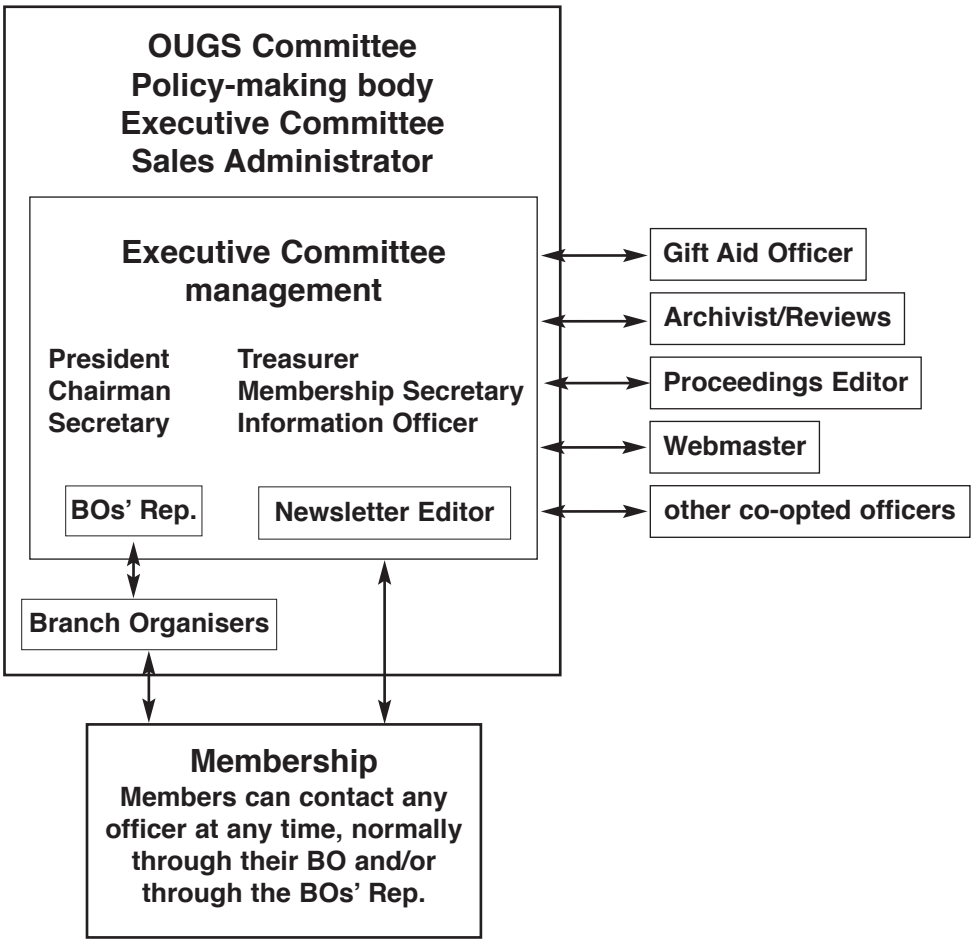

Editorial:

Dear readers,

2019 was a momentous one for The Open University, as it celebrated its 50th anniversary. The Open University Geological Society has been associated with the OU and with its various permutations of Geology and Earth Science faculties since 1972.

In accord with this long-standing relationship our 2019 OUGS Symposium was held in Milton Keynes at the OU Campus. Articles in this issue of the Proceedings *reflect that Symposium, entitled 'From the bottom of the ocean to the depth of space.'*

Also in 2019 the OUGS welcomed its newest member of the Committee, Isabel O'Brien, as OUGS Newsletter Editor. The election of Isabel has brought new enthusiasm to our Society's publications, and as an 'Editorial Team' we hope to continue to bring you interesting issues of the OUGS Newsletter *and the* OUGS Proceedings. *We have already enjoyed more than half a year of* Newsletters *under Isabel's editorship.*

With this sixth volume of the OUGS Proceedings *we bring you another collection of interesting articles emanating from our 2019 AGM and annual Symposium lectures.*

We start with adventures in volcano-lands, visiting areas in Chile, Alaska and Iceland — mixed with horseback riding, smoking valleys, grizzly bears, floatplanes and recent Icelandic sagas.

From our Symposium we explore geology throughout our galaxy and beyond. Appropriately enough, we start out on our home world, examining changing climate over the long haul, using evidence both from deep-sea sediments and ice cores to understand changing patterns and cycles in Earth's atmosphere through millions of years.

Next we peer into the depts of space, searching for other worlds of all kinds, using discoveries about their atmospheres to understand our own and how planets form.

Moving closer in, back to or own Solar System, we actually visit some asteroids, landing on them and, using remarkably designed robotic technology, begin to understand their compositions and gain insights into the formation of planets.

We continue this exploration by taking a close look at volatiles throughout our Solar System, again studying their characteristics and the composition of samples from our closets neighbour, the Moon. Bringing samples back to Earth has the advantage that some samples can be sealed away for a while, with the aim of using them in the future as our analytical techniques and technology advance to help answer new questions and gain deeper knowledge, as we are about to do with samples brought back from the Moon landings.

Then we return to basic geology, but with a twist. We learn about several ways that mountains form on Earth and compare those processes with what we are discovering about how mountains form on other planets and moons in our Solar System — on Venus, Mars, Titan and Pluto.

Studying the ancient rain patterns of the Indian Monsoon brings us not only new knowledge of how monsoons operate in general, but also knowledge to help us cope with their effects on our home world and its inhabitants.

A whole new world is explored right here on Earth in discoveries about plants: everything you wanted to know about phytoliths and silicon, but didn't know where to find out. Whoever knew they were so influential and that the study of their evolutionary development in relation to silicon had been so little known?

We visit the 'first rock from the Sun', returning after what seems to have been a long period of neglect to our little neighbour Mercury. We are brought up to date on the latest exciting explorations and meticulous mapping of its surface.

Finally, we learn about the continued search for extra-terrestrial life, focusing especially on sulphate lakes on Mars and on analogous lakes on Earth.

To complete this issue we have three Member articles. Back here on Earth, ranging widely to visit Syros in the Greek Cyclades, fossil collections in Bavaria — especially collections holding the famous Archaeopteryx *specimens — and lastly to Ireland for a field trip exploring the geology co-inhabiting the area of a popular TV series.*

Plus, there are 27 more book reviews.

As always, I wish you happy reading.

— David M. Jones, OUGS Proceedings Editor

Acknowledgements

The Editor would like to give his sincere thank-you to fellow OUGS Members who gave him invaluable help with all aspects of this issue of the *OUGS Proceedings*: to the authors for their cooperation and timely responses to my many editorial queries; to OUGS President Susanne Schwenzer, OUGS Chairman Sue Vernon and OUGS Secretary Don Cameron for their advice and encouragement; to OUGS Newsletter Editor Isabel O'Brien for her diligent proofreading; and to OUGS Family Member Anne Jones for her suggestions and advice regarding layout and design.

Note on 2019 OUGS AGM Friday evening lecture

Prof. John Mather was to deliver a lecture about the Malvern waters and springs at our 2018 OUGS Symposium at the University of Worcester. However, owing to circumstances beyond his control he was unfortunately unable to do so. Instead, Prof. Ian Fairchild presented Prof. Mather's material, and some of his own, on the Malvern springs and related. Prof. Mather's detailed abstract, prepared for the Symposium, and articles by Prof. Fairchild and Dr John Payne based on the Symposium lecture were published in the *OUGS Proceedings* for 2019 (*POUGS 5 2019*, 51–7).

Prof. Mather subsequently generously offered to give his talk on the Malvern waters at our OUGS 2019 AGM, a lecture enjoyed by all attending. Prof. Mather is continuing his research on the hydrogeology of the Malvern Hills and their spring waters, and is currently preparing a detailed paper for peer-review. This work will include a detailed assessment of the available hydrogeochemical data.

So as not to preclude Prof. Mather's new work, and with reference to his detailed abstract and the two articles by Prof. Fairchild and Dr Payne, it is thought better not to have a further article on Prof. Mather's AGM talk.

OUGS AGM 2019 Geoff Brown Memorial Lecture

Exploring unknown volcanoes

Dr Dave McGarvie, Lancaster University

Introduction

This talk will focus on the philosophy that has been at the core of my research career — finding unknown (or little-known) volcanoes, and exploring them through field campaigns. This always results in new discoveries — many of which have been new to volcanology and have thus advanced our understanding of science.

Rather than talk about research that has already been published, I have chosen to talk about two volcanoes that are the subject of my ongoing research — Quetrupillán (Chile) and Öræfajökull (Iceland). And I am also going to talk about one of the big 'unknowns' about the largest eruption of the 20th century, which occurred in Alaska, and which I visited exactly a century after the eruption began.

Outline of the talk

I will start by talking about a volcano in southern Chile that has never been mapped, and where only superficial studies have been conducted — Quetrupillán. I will also describe how, when doing fieldwork on this volcano in 2015, I had the rare experience of having my tent carpeted in tephra from a nearby volcano that erupted.

Then I will move north all the way to Alaska, and describe some of the features of the 1912 Novarupta eruption, which was the largest eruption of the 20th century. In 2012 I hiked into the eruption site exactly a century after this large eruption started.

Finally, I will shift focus across the Atlantic to the volcanic province where I have done most of my fieldwork — my beloved Iceland. Here, I will focus on just one volcano that has been showing unrest since mid-2017, and that (back in 1362 AD) produced the largest explosive eruption in Iceland since the Viking settlement *c.* 874 AD. I will describe some of the research that I have been doing on this volcano.

Figure 2 Riding into the clouds on horseback through ancient Araucaria trees (photo courtesy of Beth McGarvie).

Figure 1 The author collecting samples on one of the ridges that forms part of the Quetrupillán Volcanic Complex.

Quetrupillán, Chile

I will refer to this as just Quetrupillán, but it is known in Chile officially as Complejo Volcánico Quetrupillán (Quetrupillán Volcanic Complex). It is not one of Chile's high-altitude volcanoes, as its summit is only 2,382m elevation. The campsite I use is at an elevation of 1,600m, and to give a bit of context this is higher than the summit of Ben Nevis, which is only at an elevation of 1,345m (Fig. 1).

One of the joys of working in this area is that to get to the campsite one has to pass through the Araucaria zone (known colloquially as Monkey Puzzle trees), and seeing thousands of these ancient trees in their natural habitat is very special indeed, along with their abundant birdlife (Fig. 2).

Unknowingly, my first encounter with rocks from Quetrupillán was in 2004 when I was at a conference in Chile, and I went with a group of geologists and a Chilean guide to look at a large cliff of lava that was columnar-jointed throughout (Fig. 3). It was clear to me that there had to be ice involved in damming this lava, and in supplying the coolant (meltwater) used to produce the columnar jointing. So, my interest was piqued. And at this same conference I met a Chilean geologist (Andrés Pavez) who told me that he had just started working on Quetrupillán, and asked me

Figure 3 The cliff is entirely composed of columnar-jointed lava from an eruption of Quetrupillán, and the cliff marks a place where an ice stream dammed the lava, so the lava thickened and stalled here rather than continuing to flow. This process happens at other volcanoes, with perhaps the most famous one being 'The Barrier' in British Columbia, Canada.

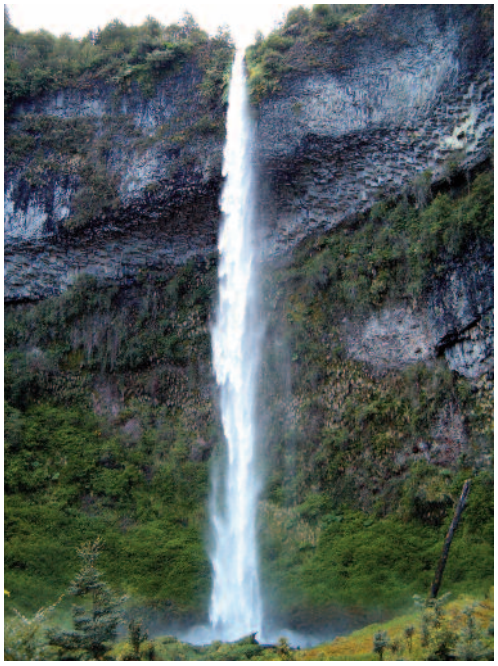

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Figure 4 "Andrés, bring the largest rock sample bags that you can get your hands on." (photo courtesy of Beth McGarvie).

Figure 5 This is Zaphira, with the author along for the ride. Zaphira had my full permission to stop and browse whenever she chose.

would I be able to help him with some of features that he thought might be related to lava–ice interactions? I agreed to help, and then after a few e-mail exchanges everything went quiet, and I did not hear from him again for seven years, until 2011, when he resurfaced having given up his study of Quetrupillán and moved into industry. However, we agreed that I would come to Chile in early 2012 to do a 'recce', with Andrés organising the trip as well as coming along on the 'recce'.

When we were organising the 2012 'recce', we had a few Skype calls to sort logistics and so on, and during one call Andrés said that he would organise the sample bags, but what size of bags would I like? Having asked technical staff in UK universities for large sample bags, and been given ones that would barely hold a 1kg rock sample, I asked Andrés to get the largest plastic bags that he could find. He surpassed himself by producing absolutely huge plastic bags, which we ended up cutting to size, and using packing tape to wrap the samples (Fig. 4).

One of the interesting aspects of working on Quetrupillán is that there is no vehicle access. So, it is a choice of a helicopter (prohibitively expensive), walking (impossible, given the amount of food and equipment you would need for upwards of two weeks in the field), or on horseback. We chose horses, and on this trip (and subsequent trips) we went up as part of an organised three-day trek that was taking other horse riders into the area, but we were dropped off with our food and equipment, and then a fortnight or so later the guides would come back with just horses and collect us and our rock samples. I am a complete novice horse rider, and was told simply to trust the horse, which I did. However, on this 'recce' and on subsequent treks there were guests who were experienced and knowledgeable horse riders who expressed concern at some of the places the horses had to go: some of them were so spooked that they got off their horses and walked over terrain that they considered too dangerous. I guess a bit of blissful ignorance can be helpful at times.

The guides also told us at the start of each trip to have a 'conversation' with the horse to let it know who was boss. On the 2012 'recce' I had a delightful horse called Zaphira, and we did indeed have such a conversation. Once we had established that she was to be boss, we got along famously (Fig. 5).

Back to the geology. Quetrupillán is in the middle of a chain of three volcanoes that are oriented obliquely to the major N–S volcanic chain that runs for nearly one thousand kilometres in this part of Chile, and along which the vast majority of active volcanoes are found. Flanking Quetrupillán are two larger volcanoes — Lanín to the east (3,747m) and Villarrica to the west (2,847m). Both are ice-capped (Fig. 6), and although there is uncertainty about whether Lanín has erupted during the Holocene, there is no doubt whatsoever about Villarrica's recent volcanic credentials, as it is one of Chile's most active volcanoes (Fig. 7, *opposite*), and it is also one of only a handful of volcanoes across the globe to have an active lava lake within its summit crater. While both Lanín and Villarrica are classic pointy and 'cone-shaped' stratocones, Quetrupillán looks as if it once had a similar pointy cone shape but lost its upper third, though we do not know whether this actually happened (i.e. during an eruption or a landslide), or whether it just grew without developing a pointy cone. The lack of a pointy cone may have led to the indigenous Mapuche people giving it the name Quetrupillán, which means 'headless spirit'.

Quetrupillán is a volcanic complex rather than just a simple volcano, because its volcanic activity is not just focused at its stratocone — there is also an extensive volcanic field to the south where there have been many Pleistocene and Holocene eruptions (Fig. 8, *opposite*). Around the western and eastern flanks there are other Holocene and Pleistocene eruptions, so volcanic activity has been quite dispersed.

Current research efforts on Quetrupillán are focused into two strands: one on the Holocene (i.e. the period since the ice retreat

Figure 6 The prominent volcano in the background is Lanín (3,747m / 12,293ft). In the middle distance is Quetrupillán (2,360m / 7,743ft), a truncated stratocone (i.e. its top is either missing or has not developed). The photo was taken from the summit of Villarrica (2,847m / 9,341ft). The Chilean volcanologist is José Luis Palma, who is wearing a gas mask because of continuous venting of volcanic gases from Villarrica's summit lava lake, which colours the ice around the summit crater.

Figure 7 Villarrica in late February 2015, from the nearby town of Pucón, c. *14km to the NNW. This was one of the many small explosions before the main eruption on 3 March 2015.*

at the end of the last glacial period, *c.* 12,500 years ago, until the present day) and one on the late Pleistocene. I have a PhD student at Edinburgh (Isla Simmons) leading the Holocene strand, as this is key to understanding potential hazards from future eruptions (Fig. 9, *overleaf*); and I am leading the Pleistocene strand as it involves many excellent examples of lava–ice interactions, which is one of my areas of expertise.

For those interested in petrology, the dominant composition erupted at Quetrupillán throughout the Pleistocene and the Holocene is trachyte (63–69wt% SiO_2). But we also have small volumes of rhyolite, trachyandesite, and at the least evolved end of the compositional spectrum we have basaltic andesites (52–57wt% SiO_2). We are working on the hypothesis that basaltic andesite is the 'original' magma that fed into the roots of the volcanic plumbing system, and analytical work on Holocene samples is currently testing this hypothesis. (For reference, basalts have SiO_2 values of 45–52wt%.)

One of the most unusual morphological features of Quetrupillán is a prominent scoured zone that encircles the stratocone (Fig. 10, *overleaf*). This feature is not seen at nearby volcanoes, or indeed at any other Chilean volcanoes that I am aware of. This scoured zone comprises three components: (1) Holocene lavas with smoothed and striated surfaces (i.e. linear grooves); (2) a blanket of unconsolidated sediment, ranging from fine sand to rounded to sub-rounded boulders, with the last dominant; and (3) at the terminus of the scoured zone are curving mounds of large boulders that rise up to 4m above surrounding terrain, and in places occur up to 10m high on slopes facing the scoured zone. Although this is ongoing research, our current preferred explanation is that this scoured zone is the result of ice movement from an accumulation area on the stratocone summit, and that this ice moved radially outwards, and as it did so it scraped the underlying lavas (forming the linear striae); and many of the lava blocks that were removed from lava flow surfaces became rounded during transport and were deposited at the termini of the ice streams, where they form terminal moraines. The striations on scarped lava surfaces are all radial to the stratocone summit area (Fig. 11, *page 5*), and the unconsolidated sediment is typical of a till blanket that is left behind after the ice has melted. The curved trains of boulders are inferred to be terminal moraines marking the maximum extent of the ice, and it is clear that there have been multiple events (i.e. outward moving ice streams). One surprising conclusion we reached is that the last terminal moraine appears to be the youngest, and if this happened during the most recent cold period (i.e. the Little Ice Age), then this was towards the latter half of the 19th century in Chile.

Holocene activity at Quetrupillán has produced a number of well preserved lavas, and the trachyte lavas in particular produce superb blocky lava flows. Lavas with high viscosity typically produce upper carapaces that consist of glassy and loose polyhedral blocks, which is why they are called blocky lavas (Fig. 12, *page 5*). These are distinctively different to pahoehoe lava surfaces (which are much smoother) and a'a lava surfaces (which are formed of rubbly blocks and not the smooth and glassy blocks of true blocky lava flows). The last eruption of Quetrupillán is thought to have occurred in 1872, but the descriptive account is dubious at best and lacks a convincing level of detail, plus there is no corroboration (i.e. it is just one account), so we are not convinced that this is correct.

Some Holocene Quetrupillán eruptions have been sufficiently explosive to produce sustained eruption columns, and because of the prevailing westerly wind direction this has resulted in terrain to the east being carpeted in tephra, and where roads have been constructed in valleys to the east, these have fortuitously revealed sequences of tephra and soil layers for volcanologists like us to work on. We use good old-fashioned graphic logging to record gain size variations, sedimentary structures, and so on (Fig. 13, *page 5*).

At this stage it is important to clarify that Holocene eruptions at Quetrupillán (away from the summit icefields) are essentially

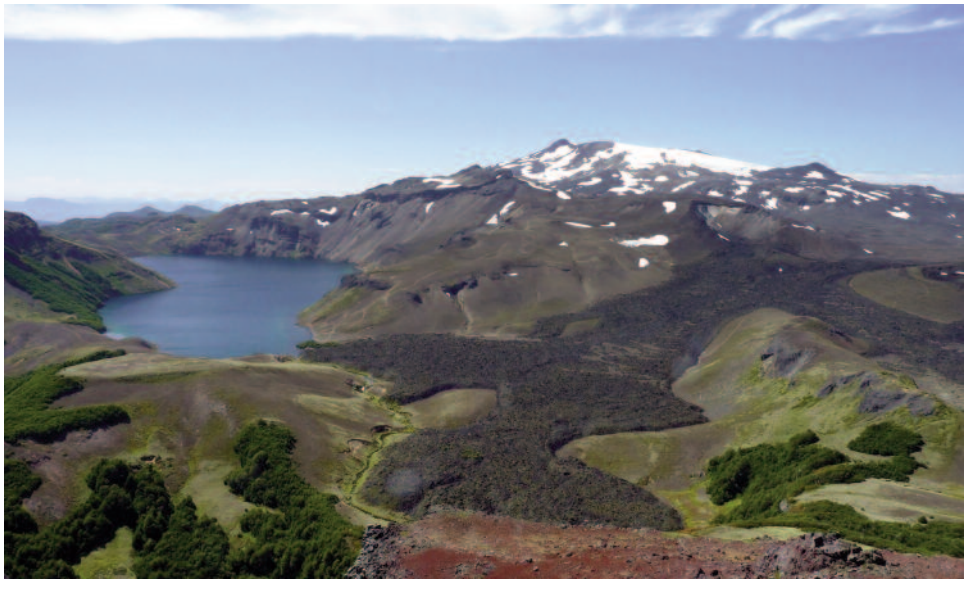

Figure 8 The truncated stratocone of Quetrupillán from the south, with Holocene trachyte lavas in the foreground that erupted from vents in the volcanic field that lies south of the stratocone.

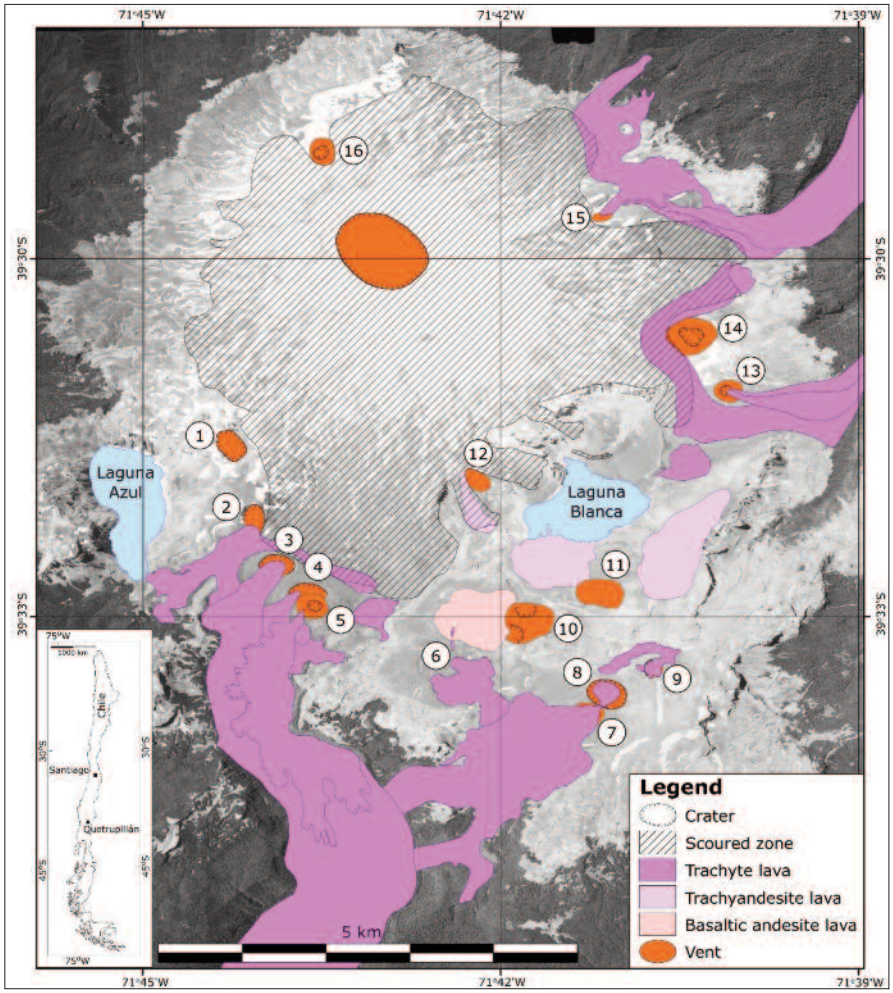

Figure 9 Geological map of Holocene volcanism at Quetrupillán, showing the 16 exposed flank vents that have erupted during the last c. *12.5ka. An unknown number of eruptions have occurred from the summit, and there may have been other flank vents within the scoured zone that were removed during the Holocene ice advances that produced the scoured zone (map courtesy of Isla Simmons).*

eruptions into a subaerial (i.e. ice-free) environment, meaning that lavas are free to flow under gravity in whatever direction is mechanically easiest, and that the lavas have distinctively blocky carapaces (as described above); and, crucially, that there is a complete absence of pervasive columnar jointing. Explosive eruption columns will spread tephra downwind, and the widespread preservation of undisturbed tephra layers clearly indicates that during deposition of the tephra, the landscape was ice-free. Tephra falling onto ice is either removed or obviously disrupted once the ice melts.

Figure 10 Photo taken within the scoured zone showing shallow dipping lavas on the stratocone's flanks that have had their rubbly tops removed, and with 5–10m wide linear gouges eroded into them. Note the superficial and unconsolidated deposit comprising poorly sorted, angular to semi-rounded lava clasts.

It is important to clarify that, apart from the local ice mass fluctuations that produced the scoured zone, there is no evidence of substantial ice around during the Holocene. This is important to emphasise, because when we move further back in time, into the Pleistocene and its glacial periods, the presence of ice changes things dramatically. Explosive products become trapped within ice vaults initially, producing piles of hydrovolcanic tephra formed through interactions between explosive eruptions and meltwater (Fig. 14, *opposite*). Lavas become confined and are unable to spread laterally, and so flow as sheets between the bedrock and an overlying ice roof (Fig. 15, *opposite*). Heat from these lava sheets melts overlying and flanking ice, which produces abundant meltwater, which in turn accelerates cooling of the lava by rapidly removing heat. Thus a major characteristic of these subglacial lavas is the abundance of columns (Fig. 16, *page 6*).

Hackles, which are small fractures, form on glassy column faces, and often reveal the propagation direction from fracture initiation (cold) to fracture termination (hot). Essentially, these small mm–cm scale hackles rather usefully yield a cooling direction, and when mapping these on the surface and interior of a lava body one can get a clear sense of how it was being cooled — from the outside to the inside, or vice versa (or a combination of the two). All columnar-jointed lavas that we have examined at Quetrupillán show a consistent pattern of cooling from the outer carapace to the inside (Fig. 17, *page 6*).

Columns are only produced pervasively where the cooling rate is high, and this requires the addition of a coolant that is more effective than air in sucking heat out of lava, which water does very effectively. It is worth bearing in mind that, under ideal conditions, one unit of basalt will melt *c.* 14 times its own volume of ice, whereas more silica-rich lavas such as rhyolites and trachytes will melt *c.* 8–10 times their volume of ice. Consequently, during protracted lava–ice interactions there is always a lot of

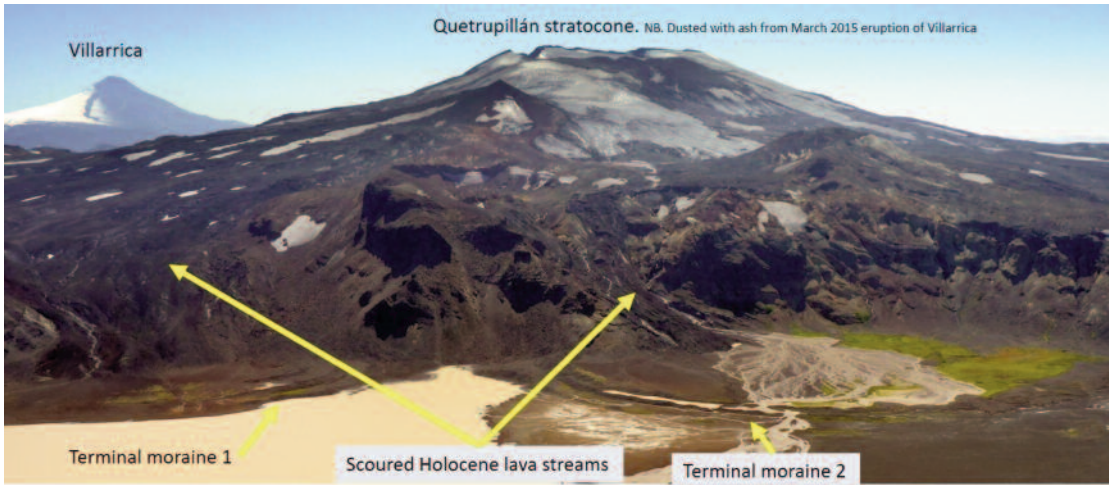
Villarrica
Quetrupillán stratocone. NB. Dusted with ash from March 2015 eruption of Villarrica
Terminal moraine 1
Scoured Holocene lava streams
Terminal moraine 2

Figure 11 Quetrupillán from the south, with two prominent, scoured lava streams that end in a series of curved and raised rides — interpreted to be terminal moraines.

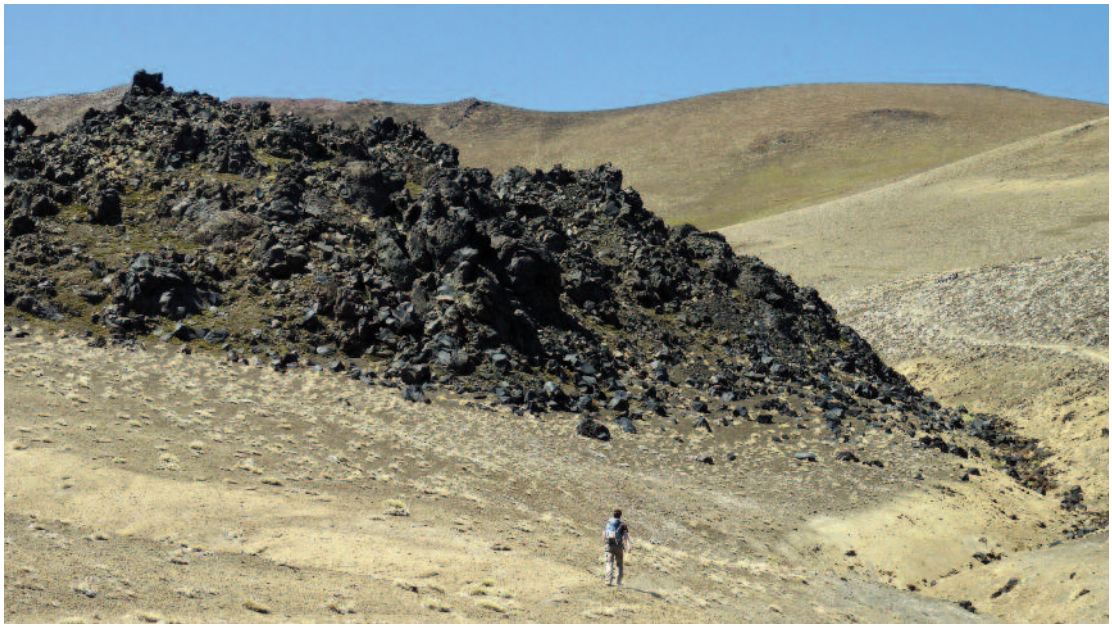

Figure 12 A typical blocky (trachyte) lava from Quetrupillán that has erupted in subaerial conditions. These subaerial lavas are characterised by upper surfaces comprising unconsolidated, glassy, polyhedral blocks. The larger rounded features in this lava are where lava 'breakouts' occurred as molten lava within the interior of the flow broke through and advanced. This is how such flows propagate.

Figure 13 In the Trancura Valley to the east of Quetrupillán are exposed a number of layers of tephra from both Quetrupillán and Villarrica. The prominent pumice-rich layer towards the top is from one of Quetrupillán's most recent explosive eruptions, though the age has not yet been determined. PhD student Isla Simmons is carefully collecting samples for lab analysis.

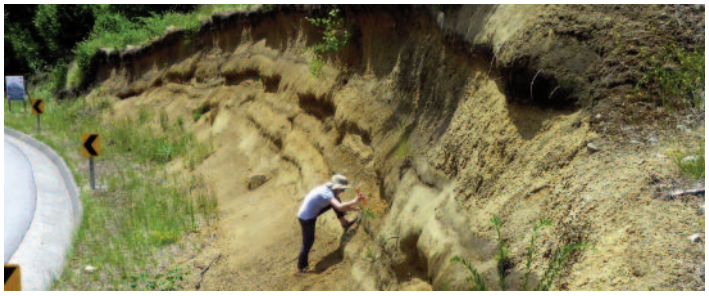

Figure 14 A pile of hydrovolcanic tephra from a subglacial eruption that occurred sometime in the late Pleistocene. The lavas above are from the same eruption, though confined to this proximal vent location by the presence of nearby ice. The lava represents a change in the eruption from explosive to effusive activity.

Figure 15 The end of a lava sheet that flowed at the interface between the bedrock and overlying ice. The upper parts of this lava sheet are glassy and pervasively columnar jointed.

Figure 16 Detail of one of the lava sheets, illustrating the glassy and radiating columnar joints on the outer surface of the sheet. Hackles on column sides indicate that cooling occurred from the outside of the sheet towards the interior (see Fig. 17).

Figure 17 This is the side of a glassy trachyte column from the lava sheet in Figure 16. The horizontal lines are at right angles to the column length, and they form due to step-wise cooling. Put simply, there is episodic (step-wise) fracturing with fractures propagating from colder (brittle) lava into hotter (ductile) lava, which blunts the fracture tip and prevents the fracture continuing. The horizontal line is the start of each new fracture: on this, there are small hackles (fractures) that start at the horizontal line and then taper to nothing; on the lower horizontal line you can see the hackles start just below the line and then taper off as you trace them downwards. Thus, the fracture is propagating downwards; and this gives us a cooling direction, which here is from top to bottom.

water (i.e. meltwater) around to remove thermal energy from lavas and thus cool them more rapidly.

As an aside, where meltwater from eruptions beneath ice becomes trapped, this increases the hazard potential as the sudden release of this meltwater (especially if unpredicted) can cause loss of life as well as inflict major changes on the environment in the pathways of such floods. In Iceland they are called jökulhlaups (glacier leaps), but the general term is Glacial Lake Outburst Flood (GLOFs). However, at the sheet-like eruptions of trachyte beneath ice that are described here, meltwater is seldom trapped in any volume, and instead it migrates away rapidly owing to the higher angle of dip on stratovolcanoes, and also because thinner ice (>100m) is less able to 'trap' water hydraulically.

While at Quetrupillán in 2015, with my Ph D student and field assistant Jonathan Moles (who helpfully gave the Geoff Brown memorial lecture in 2018, while I was recuperating from an accident that occurred at Quetrupillán), we had the unusual experience of having our tent coated in tephra (i.e. ash and lapilli) from a nearby eruption. The very active volcano of Villarrica lies only *c.* 20km away, and there had been small summit explosions for a few weeks, many of which had carpeted just the upper parts of the ice-capped stratocone in tephra.

One day it started raining heavily and I ended up moving from my hammock into the tent that Jonathan used. It hammered with rain during the night, but in the morning we discovered that it was not just rain that had been hitting the tent. On a bright 3 March 2015 morning I awoke and went for my wash, then spotted that my soap looked odd, with black particles on it. Then I noticed that these black particles were also on all of the vegetation, on the tent, and carpeting the ground (Fig. 18). A quick hand-lens inspection revealed beautiful frothy textures in the ash and lapilli clasts, and this could only mean one thing — that Villarrica had had a large eruption during the night! So, a quick change of plan was required, and instead of a long hike to the east we ascended the ridge to the west that blocked a view of Villarrica from our campsite.

Figure 18 Ash clasts (on bar of soap) from the 3 March 2015 Villarrica overnight eruption. The largest clasts found at our camp were lapilli up to 13mm.

On the ridge crest we enjoyed a few hours mapping a dyke and associated effusive features (actually ice-contact lavas) (Fig. 19, *opposite*), accompanied by frequent gazes at Villarrica where there had clearly been a substantial explosive eruption (Fig. 20, *opposite*), involving tephra deposition and surface ice melting that produced small lahars. Having no means of contacting the outside world, we did not know whether any substantial lahars had been produced, but we were confident that if any had that early warning systems would have allowed evacuation of any villages and towns in lahar pathways. We learned afterwards that there were precautionary evacuations from some places, but no substantial lahars were formed and so there was no major damage to property, etc.

After this eruption the summit icefields of Quetrupillán were distinctly 'dirty' looking because of the thin blanket of tephra carpeting them, and in the lake below (Laguna Azul) we saw a very rare phenomenon — a raft of floating tephra gradually moving southwards, driven by gentle north-westerly zephyrs. At the end of our day this tephra had accumulated at the southern end of the lake, and could be picked up by the handful. Rather special (Fig. 21, *opposite*).

To conclude the Quetrupillán story, two papers are currently being written on Holocene volcanism and two on Pleistocene lava–ice interactions. If accepted for publication after peer review they will all be published in 2020–21.

Novarupta, Alaska

The 'unknown' aspect of Novarupta is that we are still not absolutely sure where the magma came from that in 1912 fed the largest eruption of the 20th century. It is a huge puzzle.

Getting to the site of this massive eruption is not straightforward, but the last part of my journey was a bit special — a flight

Figure 19 When we reached the ridge crest that lay to the west above our camp, we could at last see Villarrica and the effects of the eruption that occurred eight hours earlier. A Pleistocene dyke is in the foreground, with Jonathan Moles examining it. This dyke is one of a pair of dykes that broke through the bedrock and encountered overlying ice. When this happened, the uprising magma formed a chain of small subglacial domes and lobes (i.e. all the eroded lava mounds in the image).

on a floatplane. And the base from which we hiked into the volcanic wasteland formed in 1912 is a fascinating place (Brooks Camp) (Fig. 22, *overleaf*). The river and waterfalls adjacent to the camp are featured in many documentaries, as the area is famous for being a great place to observe Grizzly Bears catching salmon at the waterfalls, sometimes in mid-air.

After landing, we went straight to a lecture room where we were told about Grizzlies and what to do should we encounter one, as this was highly likely at this time of year. We were told about an old male and a young female who often wandered among the cabins, and to quietly open the cabin door each morning to check whether they were sleeping on the decking outside. There was the usual bear-aware practices to follow: always making noise when walking in scrub and woodland to give the bear an opportunity to get out of the way; not leaving anything edible outside the cabins (which includes footwear and smelly socks); and if a Grizzly was suddenly encountered on a path, to back away while talking, ideally at an angle so the bear can more easily tell that you are retreating and posing less of a threat with every second that passes (Fig. 23, *overleaf*).

Figure 20 Villarrica c. *8hr after the 3 March 2015 eruption.*

And so on 6 June 2012, we hiked into The Valley of Ten Thousand Smokes exactly one century after the 1912 eruption started (Fig. 24, *overleaf*). It was called The Valley of Ten Thousand Smokes by one of the first geologists (Robert Griggs) who in 1916 entered the area some four years after the eruption, to discover a flat and wide valley flanked by steep and snow-capped mountains, carpeted with pyroclastic material (tephra), and dotted with an innumerable number of vents producing water vapour (Fig. 25, *overleaf*). The guides who took the first geologists into the area remarked that this flat-lying steaming plain now occupied what was once a steep-sided valley with a major river running through it, and that *c*. 200m of the valley had been infilled by this new pyroclastic material (Fig. 26, *overleaf*)! Although indications of the magnitude of the eruption were known from the evacuations of coastal villages that suffered heavy tephra fall soon after the eruption started, this was the first indication that anyone had of the amazing landscape changes that had occurred near the site of the eruption.

Research carried out in the decades after the eruption began to recognise that this thick accumulation of tephra was not found anywhere else, so it could not simply be sedimentation from a sustained eruption column, otherwise other areas near the vent would also be filled with tephra of similar thickness — which was clearly not the case. Detailed work on clast size distributions eventually led to the conclusion that the vast bulk of the tephra that filled this valley was in fact deposited from pyroclastic flows, which some volcanologists prefer to give the more technical (but long winded) term 'pyroclastic density currents', or PDCs for short. Clearly, the evidence pointed to the fact that there had been a preferred lateral transport of the PDCs towards the WNW from the eruption site into this valley.

Figure 21 The main photo shows the pumice raft moving left-to-right down Laguna Azul, with the Quetrupillán stratocone in the background. Note the dirty-looking snow patches and ice fields, which have a thin blanket of tephra from the Villarrica eruption of earlier that morning. The inset photo was taken much later in the day after all of the pumice in the lake had been moved to the southern end. Here, handfuls of ash and lapilli tephra could be picked up from the water.

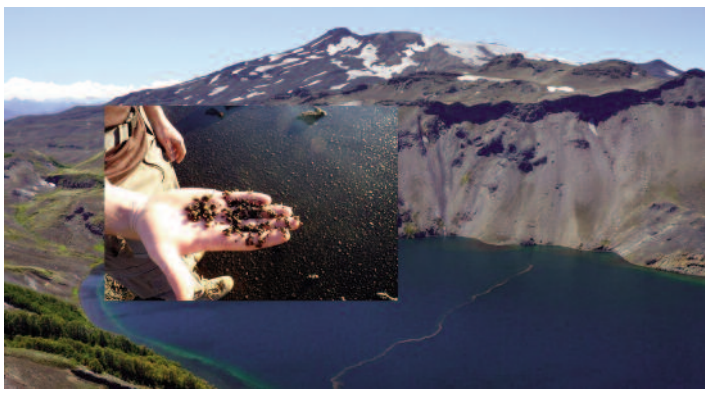

Figure 22 A floatplane arriving at the access point to Brooks Camp, Katmai National Park, Alaska.

Some of the PDCs can clearly be seen on the edges of the valley, and also where creeks have incised into the upper parts of the *c.* 170m of tephra. The deepest creeks have managed to cut *c.* 70m into the deposit, forming dangerous slot canyons that one can just about jump across, or use snow bridges to cross early in the season. We crossed a few snow bridges, but having had a very substantial one collapse beneath me the previous year at Grímsvötn in Iceland and barely escaping with my life, I was a tad uncomfortable crossing any others.

Incision that is *c.* 70m into what is essentially an ignimbrite sheet is in fact quite a lot of erosion for one century, but downcutting will occur at a much slower rate in the future as — with depth — more strongly welded material will be encountered. Put simply, as the entire eruption only lasted *c.* 60hr, and this meant that a great deal of thermal energy was retained by the pyroclasts

Figure 24 Near the start of the hike into The Valley of Ten Thousand Smokes, though after a century of cooling there are now just a few warm spots and no steam vents.

within the PDCs that filled this valley, leading to progressive welding of the interior — with the most strongly welded material at the base (where most heat was available), and with progressively less welded material towards the top. In essence, this is an ignimbrite sheet, and like many ignimbrite sheets it is formed of multiple PDCs that, after deposition, thermally stabilise and cool as one single sheet.

It was *c.* 9 miles (*c.*14.5km) to hike to base camp at the Baked Mountain Huts, which had just emerged from the snowpack, as there was a heavy late snowfall in late Spring in 2012. The huts were in a sorry state (Fig. 27, *opposite*), leaking and fairly 'manky', so many of us stayed in the tents that we had carried up. This was

Figure 23 A young and lean female Grizzly nicknamed 'Tundra' — very ungry and in need of protein. She was often seen in and around the cabins of Brooks Camp.

slightly unnerving once we found out that Grizzly Bears frequently passed near the camp as they migrated from the coast up to the salmon-rich feeding grounds near Brooks Camp — something they did before the eruption, and continued to do so once the eruption ceased. Going out for a late-night pee one would sometimes see a Grizzly walking as close as a 100m to the camp, but they were not really interested in us — they had 'bigger fish to fry' in the streams to the north-west.

However, the early expeditions made good use of the abundance of migrating bears, by using them as an important source of protein. And they also put the vigorous steam vents to good use, by lowering packages of bear meat into them to be cooked (Fig. 28, *opposite*).

As well as the amazing sight of The Valley of Ten Thousand Smokes, the early explorers recognised two other striking volcanic features that were somehow linked to this large eruption, though exactly how they were linked was not obvious. One was a small *c.* 300m diameter rhyolite dome, vigorously steaming, where no volcanic feature had existed before — appropriately,

Figure 25 The Valley of Ten Thousand Smokes as it was in 2015, some years after the eruption (USGS image).

Figure 26 At the edge of the valley, the contact between the original valley slope and the last-erupted pyroclastic flow (PDC) can be seen, with the pyroclastic flow thinning towards the pre-existing slope. The pyroclastic flow would have moved from left to right down the valley.

Figure 27 The Baked Mountain huts with The Valley of Ten Thousand Smokes behind them. It is worth bearing in mind that the flat-lying plain occupying the apparent valley floor is the top of an ignimbrite sheet that is up to c. *200m thick in places.*

Figure 28 Early expeditions took advantage of migrating bears and used them as a food source, and also used the steam vents to cook their food (images courtesy of University of Alaska Anchorage, Archives and Manuscripts).

it was named Novarupta (Fig. 29). The other feature was much more dramatic — *c.* 10km away from the Novarupta dome was the once mighty Mount Katmai; and it had lost its top, which had apparently sunk without trace into an underground chasm, to leave a *c.* 250m deep crater that was vigorously steaming and jetting out mud in 1913 (Fig. 30). The conclusion reached was the obvious one: that Mount Katmai was the source of the eruption, and that the collapse of the upper part of Mount Katmai into an underground void was caused by evacuation of a magma reservoir beneath Mount Katmai, with this magma erupting explosively from Mount Katmai to produce the tephra fall that had forced the evacuation of coastal villages, and that also produced the PDCs that filled the valley that became known as The Valley of the Ten Thousand Smokes. 'Case Closed' surely?

No. Careful mapping of the deposits revealed that Mount Katmai was definitely not the source of the eruption. A fundamental characteristic of explosive eruptions that produce eruption columns sedimenting tephra (i.e. fall deposits) is that the thickest deposits always occur around the vent. Volcanologists can easily map the thickness of a tephra deposit in many places, and then by drawing lines of equal tephra thickness (isopachs) it becomes obvious where the source vent is (i.e the bullseye). For the 1912 tephra fall, the surprising but crystal-clear finding was that instead of Mount Katmai, the vent was in fact the innocuous little *c.* 300m diameter Novarupta dome — which more detailed work discovered was sitting in the middle of a massive *c.* 2km vent that had been infilled with the last-erupted tephra.

Figure 29 The c. *300m diameter rhyolite dome of Novarupta, still vigorously steaming three years after the eruption (image courtesy of University of Alaska Anchorage, Archives and Manuscripts).*

And now we come to the 'unknown' theme of this talk. Why did *c.* 13km^3 of rhyolite (and dacite and andesite) magma come to erupt at Novarupta where previously there had been no volcano? Because this is extremely unusual! Collecting this large volume of eruptible magma typically requires a substantial and long-lived volcanic edifice that has a substantial and mature subsurface plumbing system beneath (Fig. 31, *overleaf*).

The 'official' explanation by the USGS is that all of this magma was stored beneath Mount Katmai, and for some mysterious reason, rather than take the path of mechanical least resistance and erupt at Mount Katmai itself, it decided to make the mechanically arduous *c*. 10km lateral journey underground and to erupt at Novarupta. A number of highly respected geologists do not agree with this official explanation (including the two leaders of the trip, who are senior US geologists), and point to major problems with the 'official' explanation, such as exactly how does such a high-viscosity magma (especially the high-silica rhyolite) move for such a long distance laterally through the crust? Additionally, the geochemical evidence does not quite add up, as the magma that vented at Novarupta is, in several key aspects, unlike the compositions of magmas that had been erupted at Mount Katmai in the past. And we know from many geochemical studies that each individual volcano (or volcanic system) produces its own distinctive geochemical fingerprint. These are the two major problems.

Mount Katmai is a beautiful place, and its crater now contains a growing crater lake that seems to never freeze because

Figure 30 Mount Katmai in 1913. It had lost its summit region, and in place was a vigorously steaming crater. A number of mudflows emanated from the crater rim (image courtesy of Alaska State Library — Historical Collections).

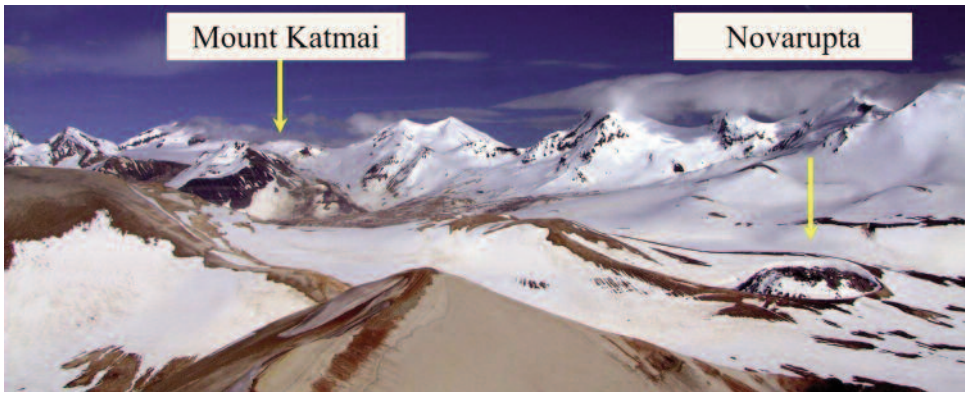

Figure 31 The geometric relationship between Mount Katmai (in the clouds) and the small rhyolite dome of Novarupta: they are c. *10km from each other.*

upwellings of warm water keep patches of the lake ice-free (Fig. 32). At some point it is predicted to overtop the crater rim, and when it does there will be a large flood as the escaping water will down-cut into the crater wall and allow more and more water to escape. Glaciologists find Mount Katmai fascinating for an unusual reason, as the collapse in 1912 'beheaded' a number of alpine (valley) glaciers by cutting them off from their accumulation areas, so their fate is being watched with interest. Heat is still also escaping from the Novarupta rhyolite dome, and one needs to be careful when walking on the areas of snow within the dome, as sudden collapses into steam-melted voids do occur, as I discovered to the amusement of my colleagues.

In summary, there are still unknowns about the precise origin(s) and journey(s) of the magmas that broke through the crust at Novarupta — a location where no eruption had occurred before, and yet produced the largest volcanic eruption of the 20th century.

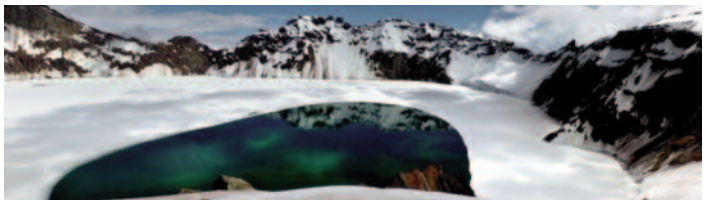

Figure 32 The growing lake within the summit crater of Mount Katmai.

Öræfajökull, Iceland

Öræfajökull is Iceland's largest volcano, and is considered by some to be the second largest volcano in Europe, after Etna. It also contains Iceland's highest land, at 2,110m elevation, which ironically is a rhyolite dome (Fig. 33); ironic because Iceland sits astride a mid-ocean ridge — and we all know that mid-ocean ridges erupt only basalt. But Iceland is not just an above-land segment of a normal mid-ocean ridge, as it also contains a mantle plume, and the on-land rifts that represent the trace of the mid-Atlantic ridge keep shifting — all of which contributes to a much thicker crust (up to 40km) than normal oceanic crust (*c.* 8–10km). A consequence of this thicker crust is that it affords more opportunities for magma to stall and cool, be reheated and recycled, etc, and this helps to explain why rhyolites in Iceland's rocks account for *c.* 10–11% of erupted rocks, whereas at mid-ocean ridges rhyolite is extremely rare indeed

There are some volcanoes in Iceland that erupt an atypically high proportion of rhyolite, and Öræfajökull is one of them. The volcano itself rises *c.* 2km above the coastal plain, and its upper half is ice-covered. At its summit is an oval 4–5km caldera filled with up to 540m of ice, but the eruption(s) that formed this caldera are unknown. In fact, although a reconnaissance geological map exists, the geological evolution of this volcano is largely unstudied, and thus it fits into the 'unknown' theme of this talk.

Only two historical eruptions are known, and in Iceland 'historical' means since the Viking settlement of *c.* 874 AD. The most recent recorded eruption was a small venting of intermediate magma (trachyandesite) in 1727–28, for which a reasonable eyewitness account was provided by a local clergyman. However, this account failed to describe where the actual vents for this eruption were, and it was long assumed that they were high up on the volcano and had since been covered by ice. In 2008 I was with a PhD student high up at the ice margin, mapping the older rocks of the volcano, when we came across the remnants of two youthful scoria cones, partly covered in glacial debris. An analysis of this scoria suggests that these were two of the vents from the 1727–28 eruption (Fig. 34, *opposite*). We never published or publicised this finding, so it was amusing to see an announcement in the Icelandic press in 2017 that an Icelandic research team had 'discovered' these same two scoria cones and identified them as belonging to the 1727–28 eruption.

This 1727–28 eruption is notable for being one of the very few eruptions in Iceland that has caused fatalities. Three people are known to have died, and they were seen clinging on to the roof of a hut that was carried away in a jökulhlaup (glacial outburst flood). The body of one woman was found afterwards, and there is a gruesome description of the flesh coming away from the bone as if it had been baked, which indeed it had been in the hot water and mud of the jökulhlaup. Incidentally, this is also one of the very rare examples of hot water being witnessed (and experienced) during an Icelandic eruption, almost certainly due to efficient magma–ice/meltwater interactions, followed by rapid transport of hot water down the slopes of the volcano. Most Icelandic subglacial eruptions involve protracted travel of meltwater beneath ice to the ice margin, and during this journey any heat in

Figure 33 Öræfajökull volcano, Iceland, rises c. 2km above the coastal plains in southern Iceland, and the upper half is ice-covered. The rocky highest outcrops at the summit lie on the rim of an ice-filled caldera.

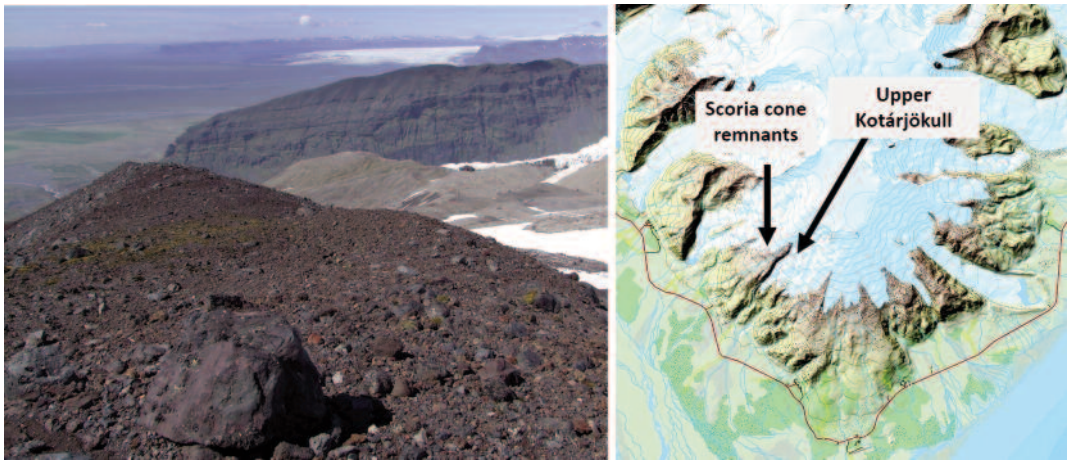

Figure 34 Left: image shows the remnants of one of the scoria cones from the 1727 eruption, which has been partly eroded by Holocene ice advances, and which also deposited some unconsolidated till. Right: image shows location of the scotia cone remnants, along with one of the major routes for eruption-related flooding that was witnessed in 1727.

meltwater is used up in enlarging tunnels, so that when it emerges the water has cooled and is just 4˚–5˚C.

I have mapped a fair amount of this massive volcano, and one of its most fascinating features is the abundance and diversity of rhyolite lava–ice interactions, which invariably produce buttresses and cliffs composed solely of columnar-jointed rhyolite lava. When studying these, one can enjoy the rare experience of walking across scree composed entirely of rhyolite columns (Fig. 35).

Öræfajökull has been largely overlooked by Icelandic researchers, who — by necessity — have had to deploy their scarce resources to monitor and study their more notorious and frequently erupting volcanoes such as Hekla, Katla, Grímsvötn and Askja. And if these are not enough to keep them occupied, along come unexpected eruptions such as Eyjafjallajökull in 2010, and the highly informative (but complex) 2014–15 eruption of Holuhraun — which demonstrated for the first time in the modern era robust evidence of magma withdrawal from the plumbing system beneath a large volcano (Bárðarbunga), accompanied by lateral movement of magma in a dyke for *c.* 40km to the eruption site at Holuhraun. This is a process long suspected of being pivotal in Icelandic volcanism, but this was the first time that robust measurements demonstrated that magma could move laterally for such long distances.

However, in August 2017 Öræfajökull started showing signs of unrest (numerous earthquakes from shallow depths down to *c.* 10km), and more monitoring equipment was deployed. A new evacuation map was prepared and distributed (Fig. 36, *overleaf*), and there were meetings between the various governmental agencies, scientists and the local population. The chief cause for concern was not the small 1727–28 eruption, but the previous historically recorded eruption, which occurred in 1362 AD. Why? Because this eruption is Iceland's largest explosive eruption of rhyolite during the historical period, and upwards of 220 people are estimated to have been killed by it *(see below)* (Fig. 37, *overleaf*). After the 1362 eruption the rich farming area around it was abandoned for decades owing to thick tephra carpeting the land, and a direct and unusual consequence of this is that the volcano was renamed. It was originally called Hnappafellsjökull, *hnappar* being the name for rock exposures sticking above the ice; but it was re-named Öræfajökull after the 1362 AD eruption, *öræfi* meaning 'wasteland').

A repeat of the 1362 eruption would be catastrophic locally, and it would also cause serious disruption to commercial air travel — both transatlantic and across western Europe — because deposits of the 1362 eruption suggest that it produced a powerful eruption column that penetrated up into the stratosphere (where commercial aircraft cruise).

Unfortunately, no modern and thorough volcanological study of the 1362 eruption has been published, and consequently the full impacts of a similar eruption are not known with confidence. Rather frustratingly, and knowing that this was a major 'plum' to work on, I had an OU PhD student working on this eruption long before the current period of unrest started in August 2017. He started in September 2013 and finished in April 2017, but was unable to complete a thesis. And on reviewing what he left behind, regrettably none of it was in a good enough state to be turned into something worth publishing. However, I and one of the other supervisors are in the habit of making our own (brief) notes and taking our own photographs when with PhD students, and so we are gradually piecing together something that we intend submitting as a contribution to improving the understanding of this highly complex eruption.

The 1362 AD eruption was unusually complex, with two suspected phases of phreatomagmatism (i.e. magma–water interactions, producing very small clasts from intense fragmentation)

Figure 35 Left-to-right: rhyolite columns end abruptly at a vertical face (author for scale); abundant rhyolite columns and an unusual scree composed of fallen columns; intricate flow folding in a rhyolite lava, on a small slab (50mm across horizontally).

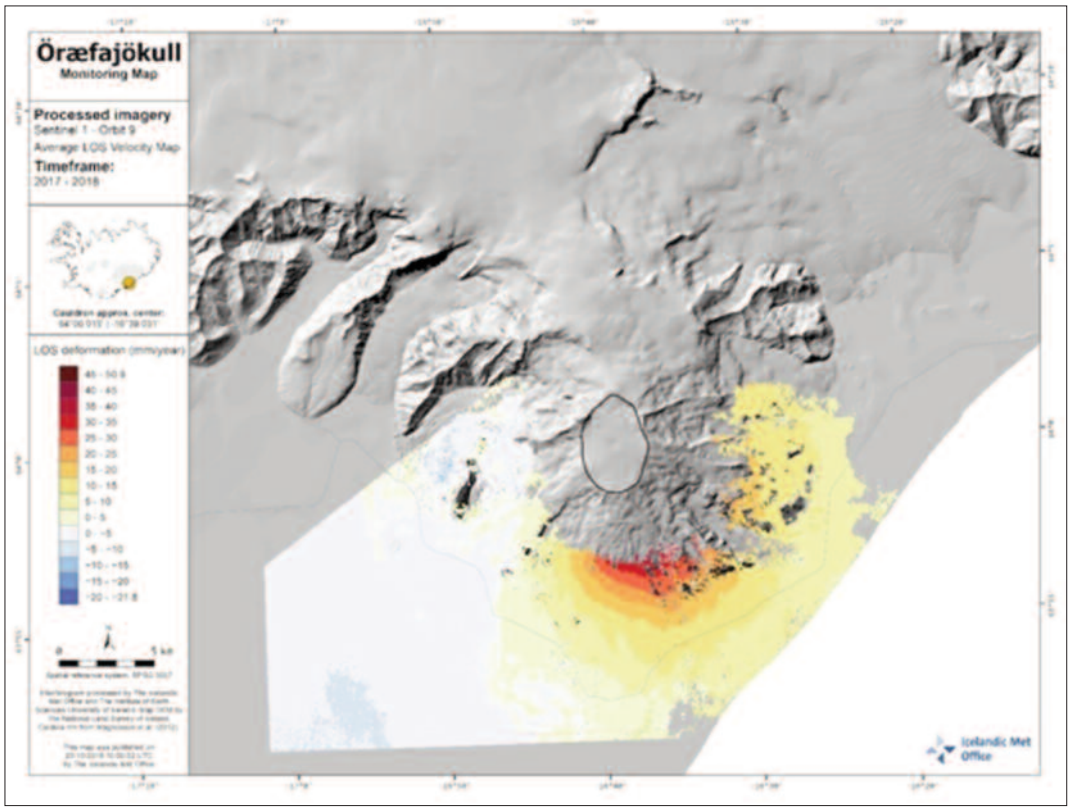

Figure 36 A monitoring map of Öræfajökull showing uplift (inflation) of the volcano in response to movement of magma into the roots of the volcano.

that either suggest two vents melting pathways through overlying ice and breaching the ice surface, or one vent with a long enough pause to permit accumulation of meltwater around the vent before the next burst of magma rose from depth (Fig. 38, *opposite*). And there are multiple PDCs that vary from dilute and relatively cool clouds descending the volcano, to more vigorous and hotter PDCs that would have killed anyone caught in their paths. There is a major fall deposit that represents sedimentation of pyroclasts from a sustained (Plinian) eruption plume that probably exceeded 20km in height; and at other times during the eruption there were weaker eruption plumes. The deposits also suggest that at times there were two different types of eruptions occurring simultaneously, with sustained eruption columns and large PDCs occurring together (Fig. 39, *opposite*).

Towards the end of the eruption, as the volatile concentration in the magma waned, glassy bombs with foamed interiors were erupted along with large lithics (fragments of conduit wall rock), perhaps representing some collapse and/or faulting. We do not know — the vent (or vents) now lie somewhere beneath the ice surrounding the summit, and are not accessible for study.

Figure 37 Left: large pumice bombs ejected during the most energetic phase of the 1362 eruption, when volatile content was very high and driving a vigorous explosive eruption. Right: glassy-skinned bombs (with slightly vesicular interiors) erupted during the waning stages of the eruption, when volatile content was much reduced, and only sporadic explosions were taking place.

In rhyolite eruptions that proceed beyond the glassy bomb phase, lava is effused, if there is just enough (gentle) degassing to push magma out of the vent to form lava. Whether this happened during this eruption we simply do not know, again because any evidence of lava effusion is buried somewhere beneath the ice. And we do not even know the locations of the vent(s), because there were no eyewitness accounts.

Although this eruption is considered to be Iceland's biggest killer of people, with in excess of 220 people killed, it is important to note that this is just a reasonable assumption made in 1958 by a highly respected Icelandic geologist (Sigurður Thórarinsson), who did a wonderful study of this eruption. He used church records (which were considered accurate, as they involved income), to identify the number of farms and hence the likely number of people working on these farms. And then he assumed that the eruption was so sudden that nobody escaped, and that nobody could have survived the heavy tephra fall, and so everyone was killed. However, Thórarinsson felt it necessary to note that not a single body was found when the area was resettled a few decades later, and that contemporary descriptions after the eruption do not mention a high number of deaths.

Modern excavations of collapsed farm buildings have likewise failed to find any bodies, and at one private excavation that I was given a tour of in 2009, the chief archaeologist said that it was striking that everything of value appeared to have been cleared from both inside the buildings and from the farms themselves (furniture, carts, etc). He tentatively concluded that people had been aware of danger, and had decided to evacuate. He pointed out to me what he considered to be evidence that some buildings had collapsed (presumably by large earthquakes) before the eruption. So, there are many unknowns about this eruption, but hopefully in the years to come there will be further work done by teams of scientists and archaeologists to turn some of these unknowns into better-known aspects of this large and very complex eruption (Fig. 40, *opposite*).

Endnote

This talk has focused on the 'unknown' aspects of three quite different volcanic areas: one in Chile, one in Alaska and one in Iceland. Hopefully it has given you a flavour of the exploration-led focus of my recent and current research, and of how this can lead to new scientific discoveries. And also a glimpse into the excitement and satisfaction that is derived when one explores unknown volcanoes.

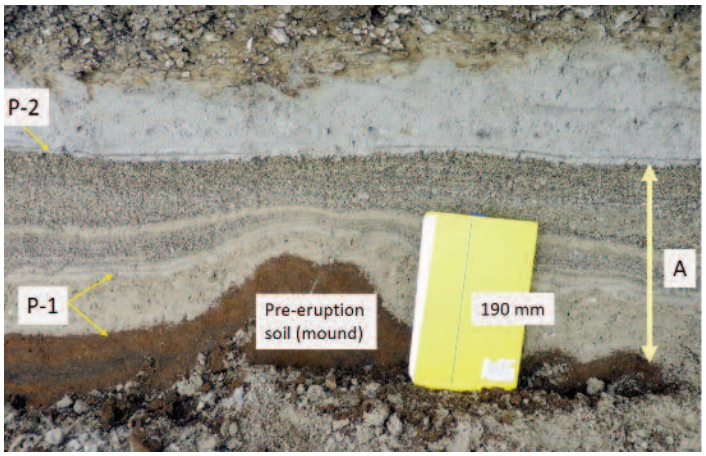

Figure 38 The opening phases of the highly complex 1362 AD eruption. The dark brown pre-eruption soil layer is prominent at the base of this section. Immediately above this is the first phase of the eruption, a fine-grained pale brown layer (labelled P-1), which I interpret as phreatomagmatic (hydromagmatic). Above this and within the boundaries of what is labelled A, the clasts generally increase in size, though with fluctuations. This suggests a lessening involvement of water with the erupting pyroclasts. P-2 marks a major change in eruptive style, with a return to phreatomagmatic activity. Note that P-2 is just the thin pale grey layer immediately below the impersistent dark grey layer. After P-2, clast size increases rapidly, again indicating lessening water involvement with erupting material.

Figure 39 After the P-2 phreatomagmatic phase mention in Figure 39, there was deposition of layers of variable thickness and colour, but crucially these layers contain structures indicating either lateral movement and/or erosion of underlying beds. These are interpreted to be deposits representing fairly weak pyroclastic flows (PDCs). The coarser top of A (see Fig. 38) is evident in these photos, as is the pale and sticky P-2 layer.

Figure 40 Photo taken in 2009 of a privately funded archaeological excavation of a wealthy (Commonwealth) farm at the foot of Öræfajökull. The lack of furniture, tools, implements, etc suggests that evacuation of the farm was planned, and that there was time to remove everything of value. No bodies were found, either of farm animals or of humans. It is unlikely that such a prosperous farm would be abandoned without good reason, and one interpretation is that there were sufficient warning signs from the volcano to justify the great upheaval that must have been involved in this evacuation.

OUGS Symposium, OU, Milton Keynes 2019: From the bottom of the ocean to the depths of space

OU Geology Society 2019 Symposium — welcome address

Richard Holliman, Professor of Engaged Research at the Open University

[The following is the text of Prof. Holliman's opening address to us — Editor]

"Good evening everyone. My name is Richard Holliman and I'm Professor of Engaged Research at the Open University. I'm also the Head of School for Environment, Earth and Ecosystem Sciences at the OU, which is why I'm here tonight to greet you. You are indeed, very welcome to this symposium.

You have a wonderful programme of activities ahead for the weekend, which is down to your President, Dr Susanne Schwenzer, and other members of the OU Geological Society. Thanks to her and the team for all the organisation.

The weekend starts with some food and then our very own Dr Marcus Badger, will deliver a keynote address later this evening. I'd like to thank Marcus for delivering this lecture; I'm confident this will be a real treat.

From looking at the programme, I see that you have other treats in store, notably Susanne, of course, but also Julia Cooke, Katrina Nilsson-Kerr, Nigel Harris, Stacy Phillips and David Gowing, all from Environment, Earth and Ecosystem Sciences.

As [a] way of introduction, I thought I'd say a few words about what I do, and how I think it connects these academics' work to your interests.

My area of academic study throughout my career has been about exploring how new knowledge relates to wider society. I'm interested in how scientists, citizens and stakeholders make sense of new knowledge.

I'm also interested in how we come to know, and how do the ways we approach knowledge production, influence who has a voice in research, what is produced, and so on?

One of the most interesting historical figures [who] has been explored in relation to these issues is Mary Anning.

As I'm sure you'll be aware, Mary was a hugely significant figure in the development of both Palaeontology and the Earth Sciences. Of course, she wasn't recognised at the time for this work, in the main because these opportunities were restricted to the landed gentry.

As a working-class woman, she had almost no voice in society, let alone [in] the sciences. Thanks to pioneers like Mary, that situation has changed. There's still much to do there, of course. But that's for another day.

Of course, Mary wasn't a trained scientist either; there weren't many of those anywhere in the world at that time. So how can we describe her. Well, I've already described her as a pioneer. In modern parlance, she could also be described as an auto-didact; in effect, she was self-taught. I argue that the most innovative scientific researchers are auto-didacts; they are creating new knowledge, but also new ways of producing that knowledge.

Mary could also be described, using modern terminology, as a citizen scientist. She contributed to the sciences as a member of the public. Her work wasn't recognised professionally, at least not in her lifetime. Attempts have been made to redress this issue. Indeed, you may be aware that Mary was recently pipped at the post as the figure to appear on the new £50 note. Alan Turing took that honour.

I think her most important contribution was as someone who broke down barriers, although I appreciate she was driven at least as much by the need to put food on the table and keep a roof over her head. For me, Mary Anning was a catalyst for profound change in how we understand the physical world around us. That, inevitably, brought her into conflict with the scientific establishment of the time.

She was a true hero, a trailblazer.

So, what's the connection with the OU Geology Society? In all these ways, I think she shares many of the attributes of an OU student, current or retired. She had a desire for new knowledge, matched by her determination and her resilience. She had a strong commitment to improve her life-chances though lifelong learning.

My point is that she reminds me quite a bit of people like you. As OU students I think you'd have got on well with someone like Mary Anning. The obvious difference is that you are not alone in your studies. You can come together at events like this, and by working together in online spaces. Through these forms of communication and engagement you can share learning, with each other, and with professional scientists like Susanne and Marcus.

I argue that the types of conflict that Mary endured, between professional and citizen scientists, can be reduced when we find way to work together in productive ways. It's in this light that I'm confident that this symposium will be a really rewarding experience for you.

I ask only one thing in return. If you get a chance, raise a glass to the memory of Mary Anning and to the OU's Earth Sciences community, both students and staff. Have fun and enjoy the weekend! Let the festivities begin…"

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From the bottom of the ocean to the orbit of Jupiter: reconstructing climate over long timescales

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The Earth's climate is changing. Of course, it always has, but this time it is human actions that are causing it to do so. To better understand how climate will change in the next 100 years, we need to know how the Earth's climate has behaved over the last 100 million years. We must use indirect measurements made from the great archive of ocean sediments, relying on chemical and biological signatures to learn more about how climate has changed in the past, so we might predict the future. In this article I explain how we must understand the movements of the planets to date and to understand the changing climate on very long timescales.

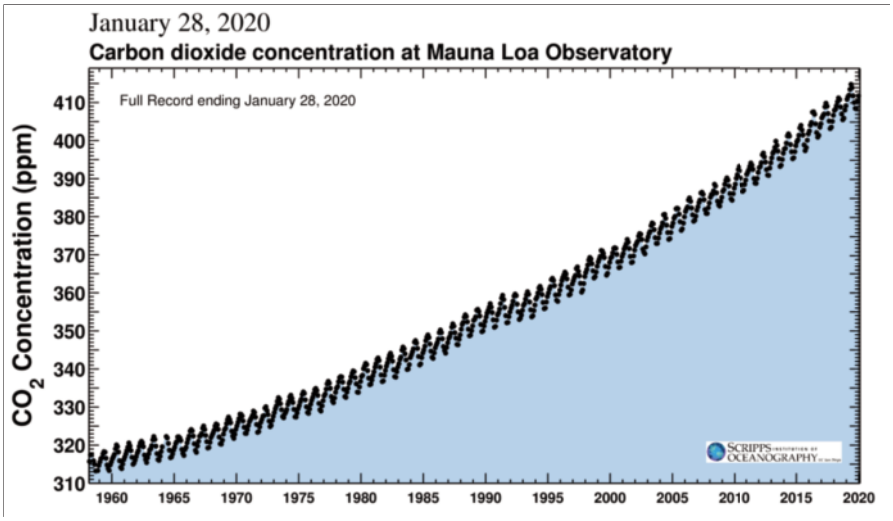
I am a climate scientist, a geologist by training, and I am a geochemist, so I use the chemistry of fossils — both carbonate marine fossils and organic molecular fossils — to reconstruct how our climate has changed on really long timescales.

But why should we care? Why do I as an Earth scientist, as a geologist, why do I care about trying to generate these records of climate try and find out what has happened in our geologic past?

Over the next 100 years we expect temperature to rise substantially due to anthropogenic greenhouse emissions; and over the same timescale we also expect global mean sea level to increase. To understand by exactly how much, we need to understand our climate system, and in order to do that we need to understand the physics; we need to understand the physics of the atmosphere, of the oceans, and on land. We can use what we know about the physics of the climate system to build computer models and run experiments, but it turns out that we also have this vast archive in the geological rock record of natural climate experiments in the past that the Earth has already run for us.

By using Earth history we can look at what has already happened naturally in the past, and by doing that we can try to understand how the climate system operates to inform what we think is going to happen by 2100; and either plan for it or plan to change that.

There are a few ways we can do this. We can look at the instrumental record of climate change, available because someone was around to measure it (Fig. 1).



One of the most important climate variables for which we have continuous measurements of is atmospheric CO_2. We have this really great instrumental record of this important greenhouse gas because researchers based at Scripps Institution of Oceanography, San Diego in the late 1950s decided that it might be important to start looking at what was happening with atmospheric CO_2. So we have this amazing record of CO_2 levels since 1958 and we can look at this in relation to the changes in temperature that we have seen over the same time interval. However, in geological terms the instrumental record only covers a very, very short space of time, and actually a relatively small shift relative to those in Earth's past. Fortunately, we can use the rock or ice records to look at these key intervals that act as natural climate experiments in the past.

Beyond the instrumental record we can use ice cores. When snow falls on an ice sheet, air gets trapped among the snow, and as the snow is compressed as more snow accumulates on top of it, the air is eventually cut off from the atmosphere. In some places, that trapped snow gets buried with the preserved atmosphere in it, and if you go to the right places you can drill into the ice, you can melt the ice, and you can get that trapped atmosphere and actually measure pretty much directly, what the CO_2 concentration was in the ancient air. If we go to the big ice domes where you have lots and lots of ice accumulating on Greenland or on Antarctica, you can use this method to get a record of CO_2 that spans the last 800,000 years of Earth history, recording the fluctuations that took place as the ice ages waxed and waned (Petit *et al.* 1999; Bereiter *et al.* 2015).

Beyond 800,000 years it is difficult to find ice from which we can trust the CO_2 trapped in it, and, critically, get an accurate age for it; and that is a problem, because for the past 800,000 years CO_2 was lower than it is today. So if we want to look into the future, high CO_2 worlds, we need to look further back in time.

We need to look for a different archive, we cannot use ice anymore, and that is where the oceans come in. We can use deep-sea sediments. Just like the snow falling onto the land and onto ice sheets, we can use sediment made up of material washed off of the continents and from the organisms that live in the surface ocean that gently drop from the surface of the oceans down to the sea floor. This enables us to get much longer records of climate change, and to look many hundreds of millions of years into the past.

Figure 1 The instrumental record of atmospheric CO_2 measured at the Mauna Loa Observatory by Scripps Institution of Oceanography SIO (unrestricted usage: Scripps CO_2 Program, with permission, Scripps Institution of Oceanography SIO. Daily updated figure at scripps.ucsd.edu/programs/keelingcurve/wp-content/plugins/sio-bluemoon/graphs/mlo_full_record.png) (Keeling et al. *2001).*

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Figure 2 The International Ocean Discovery Program's drillship the JOIDES Resolution *in port in Freemantle, Australia in 2017 after Expedition 36 (photo courtesy of M. P. S. Badger).*

To get a really long sediment archive, we need to use a big ship with a lot of specialist features. Figure 2 shows one of the main drill ships of the International Ocean Discovery Programme (IODP), a worldwide collaborative programme. With this ship we can go pretty much anywhere in the world to recover deep-sea sediments.

So, how are the planets and how are the larger planets related to any of what I have been describing so far?

To get to that part of the story, we need to think about the Earth's orbit around the Sun. The Earth's orbit is not a perfect circle. Sometimes the Earth has a nearly circular orbit — as it does today — and sometimes it has a much more elliptical orbit. This is called the eccentricity of the orbit (Fig. 3). There are also changes in the tilt of the Earth's axis of rotation relative to the plane of the orbit (called obliquity); and a third mode of variation, which is the wobble on the Earth's tilt, or precession of the equinoxes around the orbit.

These three changes in the Earth's orbit change the amount and distribution of solar radiation, that reaches the Earth's surface, and so affects the climate of the Earth. These changes in climate are preserved in the rock record: as changes in sea level, river run-off, and temperature (among other things), from which we can determine from the geochemistry and sedimentology of the rocks.

These changes in the orbit also have something else important about them — they all have a specific rhythm: eccentricity changes with a beat at 95 thousand years, 123 thousand years and 413 thousand years; obliquity changes with a beat of 41 thousand years; and the two precession cycles have beats of 19 thousand years and 23 thousand years (Fig. 4, *opposite*).

The timing of the variations in orbit is in turn controlled by the orbital dynamics between the Earth, the Moon, the Sun and the large gas planets (and this is where Jupiter in my title comes in). We can reconstruct these changes back over the past, and, coupled with some spectral analysis of the rhythmic patterns preserved in the rock record, use those orbital variations to generate incredibly accurate age models for the rocks and sediments recovered by IODP and other projects.

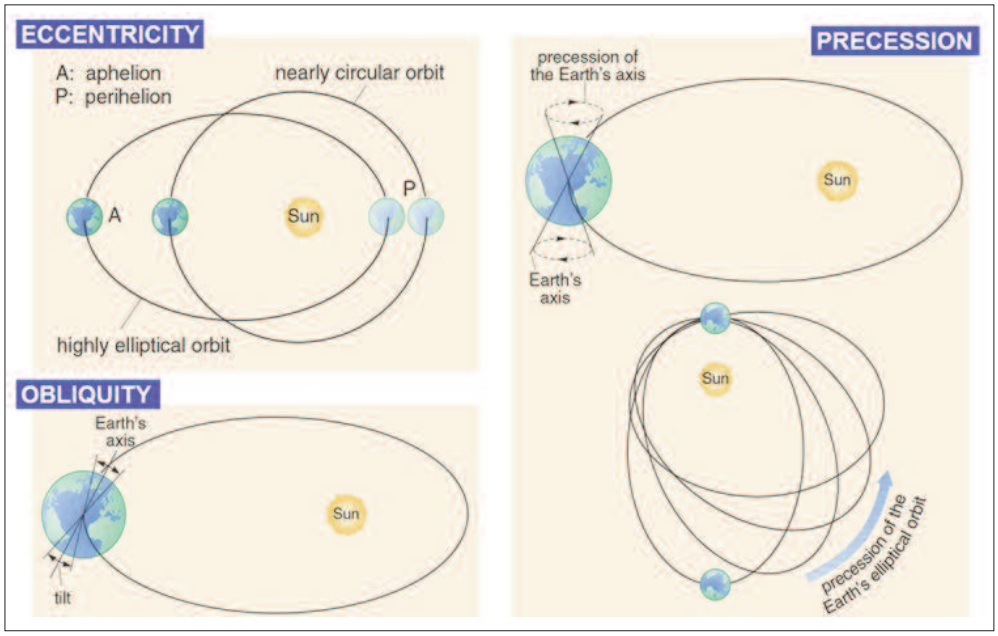
These accurate, high fidelity records of time in our sediments show us the linkages between insolation and climate, and enable us to tie together sediment records from different places, to put them all on the same timescale, and with a global climate record try to understand how climate and CO_2 and the orbit affect the climate on the Earth.

Figure 5 *(opposite)* is the Ras il-Pellegrin section, Malta, where I sampled for my PhD research (Badger 2008; Badger *et al.* 2013a). The section also contains the 'Golden Spike' for the Langhian-Serravailian boundary at 14Ma in the Miocene (Hilgen *et al.* 2009) — one a few places on Earth used to help tie together the whole of geologic time; and this one is based (in part) on orbital dating of the dark–light sediment bands that you can see in the image. An orbital age model enabled us to tie this section to other sedimentary records around the world obtained by the IODP and its predecessors.

So we have those records, we have those sediments, we have an age scale; we know when which bit of rock was laid down in the bottom of the ocean, but why do we care? What can we do with this data? Well, I am an organic geochemist, I am interested in generating those CO_2 records that we saw right at the start, but over *really* long time-scales, when you cannot use ice because none exists from 14mya when the Ras il-Pellegrin sediments were being laid down at the bottom of a shallow sea.

I can study the organic geochemistry of the sediments laid down in the Miocene to determine the atmospheric CO_2 of the time. We can do that because the plankton, which lived in the surface ocean, are sensitive to the amount of CO_2 in the atmosphere at the time, and preserve that information in the molecules that make up their biomass. When they die and settle to the sea floor, some of those molecules are preserved, along with the information about the atmospheric CO_2.

Figure 3 The three modes of change of the Earth's orbit around the Sun (from Coe, A. (ed.) 2003 The Sedimentary record of Sea Level Change. *Milton Keynes and Cambridge: The Open University and Cambridge UP, with permission).*



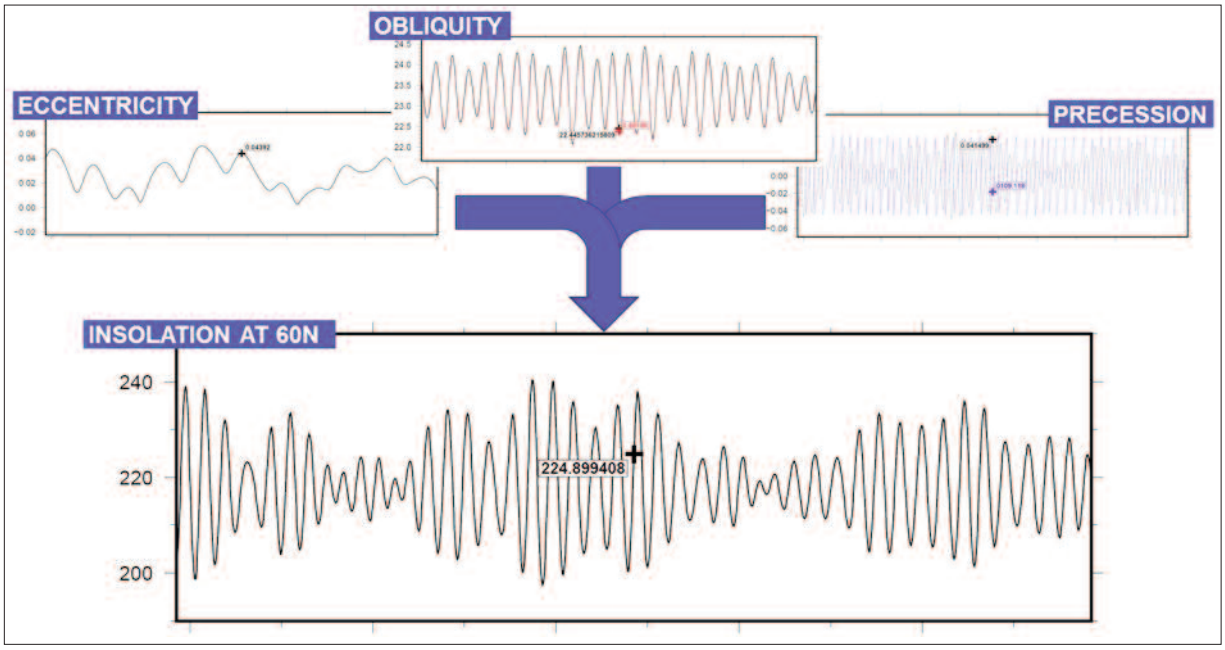


Figure 4 The beats of the eccentricity, obliquity and precession cycles combine to give a unique fingerprint to the distribution of solar radiation that reaches the surface of the Earth (photo courtesy of M. P. S. Badger).

We know from other geochemical signatures, along with sedimentary evidence, that the middle Miocene represented by the Ras il-Pellegrin section was much warmer than it is today, with less ice on the planet, but still with rhythmic orbital variations preserved in the sedimentary sequences. Coupled with the CO_2 records from my and others work on middle Miocene sediments, we can understand better how the climate system operates in a warmer, higher CO_2 (Badger 2008; Badger *et al.* 2013a; Badger *et al.* 2013b).

To study an interval closer to today, and likely more relevant to the next 100 years, many (myself included) have studied the warm Pliocene (*c.* 4Ma) as a partial analogue for future warm temperatures. Using the same geochemical methods that I had applied at the Malta site — this time from an IODP site in the Caribbean, again dated with help from the orbital cycles — we studied how sensitive the Earth's climate system is to CO_2 in a higher CO_2 world. We found that the sensitivity to CO_2 found in the climate models we use to model the future is well supported by evidence from the past (Martínez-Botí *et al.* 2015; Badger *et al.* 2013b).

Conclusions

Our climate is changing. We need to understand how, and why, and we need to know what we *can* do about it and what we *should* do about it. We can learn about the future by studying the past, by looking at the fantastic archives of natural experiments found in the sediment record. Through large, international collaborations like the IODP and IPCC, we can use ocean sediments and Earth system models to find out how climate changed in the past. We can use natural variations in Earth's orbit both to explain rhythmic changes in past climate and also to help us to provide the high-fidelity age models needed to understand our climate system with enough confidence to predict future climate change as well.

Figure 5 The golden spike for the Langhian–Serravalian boundary at the Ras il-Pellegrin section, Malta (photo courtesy of M. P. S. Badger).

References

Badger, M. 2008 'Middle Miocene Carbon Cycle Dynamics: a Multi-proxy Approach'. Unpubl PhD Thesis, Cardiff Univ; available at http://oro.open.ac.uk/46461/ and at http://orca.cf.ac.uk/54189/

Badger, Marcus P. S., Lear, C. H., Pancost, R. D., Foster, G. L., Bailey, T. R., Leng, M. J., and Abels, H. A. 2013a 'CO_2 drawdown following the Middle Miocene expansion of the Antarctic Ice Sheet'. *Paleoceanogr* **28**, 42–53; doi.org/10.1002/palo.20015

Badger, Marcus P. S., Schmidt, D. N., Mackensen, A., and Pancost, R. D. 2013b 'High-resolution alkenone palaeobarometry indicates relatively stable pCO_2 during the Pliocene (3.3–2.8 Ma)'. *Philosoph Trans Series A, Math, Physic, Engineer Sci* **371**, 20130094; doi.org/10.1098/rsta.2013.0094

Bereiter, B., Eggleston, S., Schmitt, J., Nehrbass-Ahles, C., Stocker, T. F., Fischer, H., Kipfstuhl, S., and Chappellaz, J. 2015 'Revision of the EPICA Dome C CO_2 record from 800 to 600 kyr before present', *Geophys Res Lett* **42**, 542–9; doi.org/10.1002/2014GL061957 (accessed 10 October 2016)

Hilgen, F. J., Abels, H. A., and Iaccarino, S. 2009 'The global stratotype section and point (GSSP) of the Serravallian Stage (Middle Miocene)'. *Episodes* **32**, 152–66; https://engineering.purdue.edu/Stratigraphy/references/Serravallian_v32n30.pdf (accessed 12 January 2015)

Keeling, C. D., Piper, S. C., Bacastow, R. B., Wahlen, M., Whorf, T. P., Heimann, M., and Meijer, H. A. 2001 'Exchanges of atmospheric CO_2 and $^{13}CO_2$ with the terrestrial biosphere and oceans from 1978 to 2000'. I Global aspects, SIO Reference Series, No. 01–06, Scripps Institution of Oceanography, San Diego, http://escholarship.org/uc/item/09v319r9 (accessed 24 January 2020)

Martínez-Botí, M. A., Foster, G. L., Chalk, T. B., Rohling, E. J., Sexton, P. F., Lunt, D. J., Pancost, R. D., Badger, M. P. S., and Schmidt, D. N. 2015 'Plio-Pleistocene climate sensitivity evaluated using high-resolution CO_2 records'. *Nature* **518** (7537), 49–54; doi.org/10.1038/ nature14145 (accessed 5 February 2015)

Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., Chappellaz, J., Davis, M., Delaygue, G., Delmotte, M., Kotlyakov, V. M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, K., Ritz, C., Saltzman, E., and Stievenard, M. 1999 'Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica'. *Nature* **399**, 429–36; http://www.nature.com/nature/journal/v399/n6735/abs/399429a0.html (accessed 12 January 2015)

Exoplanets

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Prof. Haswell edited her lecture transcription provided by us, but was unable to send us any figure or photographs from her talk. Following is an edited version of the text, with further editing — within [ ] — to accommodate the lack of illustrations and help the syntax — Editor.

[Introduction]

On the cover slide [Prof. Haswell showed] a very beautiful planet, one of my favourites; and it is actually a photograph that I took myself, when I was observing in the Andes in Chile. One of the nicest things about being an astronomer is that [you] do get to travel regularly to mountain tops. In fact, many of my friends, when I was a student, were geologists. After graduating they mainly got to travel to conference rooms and [to] oil rigs. So, in some ways, studying astrophysics is a great thing if you like geology.

[Prof. Haswell told us] a bit about exoplanets. [She gave us] a broad feeling for the field as a whole, but [focused on the overlap] between what we know about planets orbiting around other stars, and geology. [Her intent was to give us] a flavour of some of the work that I have been doing, which is moving towards that overlap.

On [her next slide Prof. Haswell listed] some of the people who have contributed to this work and [declared that] like all 21st-century science, I am standing here presenting it, but most of the work was done by other people and science proceeds as a team effort. You may have done some of those OU modules where you have to do group working, which many people find a bit irritating. It is, actually, a really important skill to learn for science in general, so I commend them to you!

[Searching for exoplanets]

[Prof. Haswell began by introducing us] to the first known rocky planet outside our own Solar System, and [finished with] a little quiz associated with that; so you might want to start thinking about, "What do I know of rocky planets outside our own Solar System? What was the first one that was discovered, and which telescope discovered it?" Then [I will] tell you about lava lakes and mass loss from rocky planets orbiting other stars. I will tell you a little about the demographics of planets within our own Galaxy. How common are they? What are their characteristics as far as we know [them]. And then I will tell you how I think that we can learn about the compositions of planets outside our own Solar System. What are they made of? Can we start doing geology of rocky planets orbiting other stars? And, lastly, I will tell you a little about a project that I have been leading, [a project that has been going] for about seven years now — called 'The Dispersed Matter Planet Project'. And this is [research] that has quite strong synergies, potentially with the interests of geologists.

This is the best time there has ever been to be a scientist. We live in really exciting times. Until quite recently, we did not actually know if any other stars had planets. When I was doing my PhD, it was viable to think that actually our Solar System might be unique, and [that it] might have been formed as a consequence of a rare event like two stars passing close to each other and pulling some mass gravitationally away to form planets, as that mass [settled] down. So, it was [thought] plausible back in 1990 that our Sun might have been the only star with planets. If true, that obviously has very profound implications for our place in the Universe. However, we now know that, actually, planets are commonplace and, in general, we think that when you form a star, you probably form planets, with no special requirements. So, as a gas cloud collapses under self-gravity, a bit like an ice skater spinning, material tends to get flung out, due to the laws of physics, to form a sort of disc — like an ice skater's skirt flaring out if she does a very fast spin. And, from that disc of material, carrying away the angular momentum from the young star, planets form. So, planets form with stars as a routine process. We know now that the Galaxy is full of planets.

For any astronomers who have ventured into this talk, this is not news. Stars are much bigger and brighter than planets. Astronomers work with light, so stars are quite easy for us to work with, to discover, and to measure the properties of. Planets are really difficult for astronomers to study. For example, imagine [that] you were to go outside our own Solar System and try [to] study the Earth. If you were to use optical light, i.e. the light our eyes are sensitive to, there is a factor of about 10 billion difference in brightness between the Sun and the Earth. So, it is really hard to measure any of the properties of the Earth, [as] it is being drowned out by a much bigger and brighter [brightness]. So, the whole of exoplanet science is basically getting around the fact that you cannot actually see the planets, because they are drowned out by the star[light].

There are two main methods that we have used to find exoplanets. The first one is the 'Radial Velocity Method', [which] uses the fact [that] while we think about planets orbiting around stars, from the point of view of physics, both the planet and the star are just [two] massive objects. And they are interacting through gravity, obeying Newton's laws of motion, and feeling each other's gravitational pull. In fact, both the planet and the star orbit around the common centre of mass. We cannot see the planet, but we can see the star. So, what we see is the star's very small motion as a result of its very small orbit around the centre of mass of the system. So, this is the first and one of the best ways to find planets. If you find a planet by measuring the motion of the star, through the Doppler shift of its light, that automatically tells you something about the ratio of the mass of the star to [that of] the planet: if you know the mass of the star, then you can work out the mass of the planet. Radial velocity measurement [depending] on the Doppler shift, is [useful] because it tells you how massive the planet is. [J]ust to frivolously illustrate the situation, the star is so much more massive than the planet [in] the way that the orbits are balanced around the centre of mass is a bit like a Sumo wrestler and a hamster on a see-saw. If you were to do [such an] experiment, you would find that the Sumo wrestler barely moves but [that] the hamster probably [moves] quite quickly.

The second main way that we find exoplanets is through the 'Transit Method' [demonstrated with a photograph] of the transit of Venus, where Venus passes in front of our view of our Sun. You [can] see the dark spot on the Sun's disc, where Venus is getting in the way and blocking out some of the light. [This situation]

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can also happen if we are looking at a distant star and we happen to be looking in the orbital plane of the planet — some of the planets pass in front of their star and block some of the light. This is [in fact] the [most frequent] way that we have discovered planets orbiting around other stars. You just measure the brightness of the star over and over again. If the star has a transiting planet, that will block some of the light and the star will appear to get dimmer for a little while. [We] can quite easily measure that difference in the amount of light we see from the star. And the great thing about this method is [that] by looking at the amount of light that is being blocked, you can work out the size of the planet. So, you can see that if you combine those two things; if you have a planet that transits and you measure the Doppler shift, then you know both the size and the [planet's] mass; and that [information enables you to determine the planet's] density; [and then] you can begin to actually infer what it is made of.

[Showing a slide of] the first known transiting exoplanet and of the telescope that discovered it: [This telescope] was not a particularly sophisticated piece of equipment, and [the discovery was actually made] from a car park in Arizona. All that was done was to measure a 1% dip in the light from the star and that [told us that there was] a planet orbiting around it and getting in the way.

After that [first discovery] there was a lot of interest in trying to find other examples. The Open University was part of the SuperWASP project: We bought a whole load of camera lenses and pointed them at the sky to measure the brightness of lots of stars; [we] bought camera lenses [on eBay] from a nice man in South Korea. [This work] got some national publicity in a very fine publication [shown in a slide of an article in *The Sun*].

One of the objects that we found in the WASP project [is] WASP 12b, an extreme 'hot Jupiter', [of] similar mass and size to Jupiter, but in a one-day orbit around its host star. WASP 12b actually orbits the outer part of the stellar corona — very close to the star. We will come back to WASP 12b later.

[As] geologists I do not suppose that you are tremendously interested in Jupiter-sized planets, because they are not rocky. Ten years ago, we mainly knew about giant planets, [but little] about rocky exoplanets. This is because the transits are 1% deep for a giant planet — so you can do that from a car park in Arizona. However, if you are trying to look for a planet the size of the Earth, the transits are only 0.01% deep, and that is really difficult to measure. It is actually impossible to do from the ground, because the Earth's atmosphere [affects] the light passing through it [and that] drowns out effects of [its] size. [To] look for Earth-sized planets, you need a space telescope, [so it was not until] about ten years ago [that] we found the first rocky exoplanet.

[The promised quiz]

[Prof. Haswell asked,] "Can anyone name the pioneering space telescope that discovered that planet?" "Hubble?" [was one answer from the audience]

No, it wasn't Hubble. It would have been Hubble, but the high-speed photometer was broken. Any other ideas? Can anyone name any other space telescopes that have worked on exoplanets?

Somebody said "Kepler" I think?

Well done, that was the answer I was expecting. It is wrong, [though]! Kepler has discovered loads of transiting planets and has got a huge amount of press. Kepler is a NASA mission and NASA is really good at [getting] press [coverage]. However, there was a really important space telescope called COROT, which was a French European mission and it [initially] paved the way for what Kepler has done and everything that we know about exoplanets. However, nobody really knows about it. It did not get the publicity that it should have got in my opinion.

[COROT] found the first terrestrial exoplanet — Corot 7b — [announced in February 2009]. In addition to its being a non-American mission, [and thus] not benefiting from the NASA publicity, I think that part of the reason [Corot 7b's discovery] did not get as much attention in the press as it should have done is because the principal investigator of that mission was a woman called Annie Baglin. [It seems that,] in general, people tend to assume that people in leadership positions are male and tend to get more attention; [and that this fact about the COROT principal investigator] just exacerbated the overlooking of the COROT [telescope's] results. [It is important to acknowledge] Annie Baglin's excellent pioneering contribution to [the search for exoplanets and to astronomy in general].

Corot 7b is orbiting very close to its host star. It is a rocky planet, roughly the same size as the Earth and it is tidally locked in the same way as the Moon is tidally locked to the Earth, so it always presents the same face to its host star. [Corot 7b] is actually being baked to a very high temperature in those sub-stellar regions, because it is always pointing at a very hot star from a short distance. We think that the rocky surface is actually molten, so a large part of the tidally locked sub-stellar hemisphere of Corot 7b is probably a lava lake. This is interesting, I think, from a geological point of view. If you [have] a lava lake, you might get sublimation, so you may get your rocky minerals forming a sort of silicon-rich atmosphere around this very hot planet.

[Kepler's discoveries]

What we know about exoplanet demographics and the population of planets within our own Galaxy has largely been discovered by the Kepler space telescope, which is a NASA mission. And, I have not updated [the information about Kepler in this lecture for] a few years, [but up to about three years ago] we knew of about 3,000 transiting exoplanets; [but now] we are up beyond 4,000. Transiting exoplanets are now 'ten a penny', [so we have] enough to do statistical inference on the population of planets found, and [we can] correct for the various selection effects. [We know we have not found them all — there are many exoplanets that are more difficult to find — but] now have a pretty good idea of the Galaxy's population of planets. And what we know is that terrestrial rocky planets are actually widespread in the disc of our Galaxy. Rather excitingly, they are not restricted to stars like [our] Sun, which come from fairly late-generation star formation, [and therefore] formed from material chemically enriched by previous generations of star formation. We know that there are some rocky planets orbiting stars that are 10 billion years old. So, they formed quite early in the history of the Universe. [Therefore,] we know that rocky planets have been around in our Galaxy for a long time. That is really favourable for the prospects for the development of complex life elsewhere in the Galaxy!

About 10Ga before Earth formed, somewhere towards the beginning of the Universe, the first rocky planets were formed. So it seems quite likely that evolution might have produced life elsewhere in the Galaxy. One of the categories of exoplanets that are publicised a lot are [the] so-called 'habitable' planets.

Astronomers are quite glory-hungry, and whenever we find something we try to attract as much attention from the media as possible. So, it sometimes seems that the most habitable planet ever is found once a fortnight!

[showing a slide of Kepler's discoveries] There are rocky planets that are known to be roughly the right distance from their host star to [have] a similar temperature to the Earth's. That, obviously, is a favourable situation for life as we know it. [For example], the Kepler-62 system is a system of five transiting planets. [There are dips in its star's light curve showing] where the planets [are] passing in front of the star and blocking some of the light. [By] measuring how deep those dips are and how often they occur, [we] can measure the size and the orbital period [the planet's 'year'] for [each] planet. So, really all we know about them [are] their sizes.

[Finding nearby rocky planets]

[Most of] the exoplanets we know about orbit stars in our own Galaxy, and we think that from a distance our own Galaxy looks something like a spiral galaxy. [showing a slide tabling exoplanets discovered]

Most of the planets we know about were discovered by Kepler, and they are represented by that white dot [on the slide]. [Many other planets have been discovered by the La Silla observatory in Chile.]

Kepler is just staring in a particular direction, at a particular point in the sky. So, most of the stars that it is looking at are quite distant, [and thus] appear faint. So, it is difficult for us to do detailed measurements to learn a lot about them. And, looking to the future, [their distances from Earth will of course make them] even more difficult for us to visit. So, for these reasons it is important that we find nearby examples. [On the slide] our Sun is on the left-hand side, and the green dots are the typical distances of planets that have been discovered by the Doppler wobble, which requires really high-quality data; the red dots [show] the typical distances of planets discovered by transit projects like SuperWASP, which works from the ground.

So, we really want to find nearer examples with high-quality space photometry to find nearby rocky planets. In fact, NASA is doing this right now [in] a project called TESS — a new NASA mission — that is going to find planets orbiting nearby stars. It is focusing on bright stars that are close to us, but it is only going to look at each patch of the sky for 30 days. So, it will not find planets like the Earth, because you need to observe for three years — basically to see a transit three times — to know what the orbital period of the planet is. TESS [it is hoped] is going to find a lot of short-period terrestrial planets.

However, [another project, called] PLATO, is really going to find exo-Earths. PLATO is a newly approved ESA European Space Agency (ESA) mission, and it is going to [search for] planets orbiting bright, nearby stars, [observing] longer orbital periods [to look for exoplanets] that are truly analogues to Earth. The [original] launch date [for] PLATO [has slipped, and is now set for 2027].

[Wild and wacky exoplanets]

I will now tell you about some 'wild and wacky' exoplanets. [Referring] back to Corot 7b and similar close-in, very hot, rocky planets, the [surfaces] of these planets [are] heated to *c.* 2,000˚C *[Centigrade, added by the Editor, is assumed]* [owing] to the proximity to [their] host [stars]. The rocky surface sublimes into gas and then is boiled away from the planet, so in physics jargon, you get a thermal Parker-type wind, which flows out from the surface because the sublimation creates pressure. And as that happens, the very metal-rich gas, which is basically vapourised rock, can then have dust condensing out of it.

Kepler found [an] interesting planet that has transits of a dust cloud being formed from [it] and is orbiting around the star with the planet. The dust cloud [comprises] material being lost from the planet. We know it is a dust cloud because the starlight is regularly blocked by something opaque passing in front of the star; however, each time [this] happens, the amount of light that is blocked is different. In two measurements *c.* 1% of the star's light [was] being blocked, and then only 0.2%. It is hard to imagine what [phenomenon] other than a dust cloud could do that. You could not have a rigid body or a system of rigid bodies that is able to change its size and shape every 16 hours or so! So, we are pretty sure that this is a dust cloud passing in front [of the star] and regularly obscuring our view of [its] starlight. That is interesting, because if you have dust that is scattering light, you can actually look at the properties of that as a function of the colour of the light, or the light's wavelength, as physicists call it. That [information] can actually tell you the composition of the dust, [using a] complicated mathematical theory of how light is scattered by particles, and [depending] on the composition of the particles. [A] plot shows iron and corundum, and forsterite and enstatite — [all] different minerals. So, by interrogating the light [seen] from [a] planet-star system, you can begin to learn about the mineralogy of the planet. This is a planet that you cannot actually see, but [whose effect on its start starlight you *can* see].

This particular object is in a short-lived, catastrophic phase, where its rocky surface is being boiled off, happening in about the final 1% of the planet's total life. [And this phenomenon] is not unique. We know of at least two other examples where something similar is happening. So, this seems to be part of the general story of the life cycle of rocky planets in our Galaxy. And we think that there must be examples fairly close by. [At] the end of [this article] I will tell you how I think we might find some of them.

[With one of my PhD students,] we measured the transit of [the planet's] dust cloud in three colours. [The measurements enabled] us to start learning about [the] size of the dust particles and their compositions. [We] have a really nice data set, [and] a lot more of these measurements yet to be analysed. We [also] did some modelling. We fed [in] some mathematical models and [drew] some conclusions. We discovered that the dust [formed from the planet's mass and orbiting the star with it] has larger grain sizes than the typical dust from the interstellar medium.

[Planetary atmospheres]

[I will now] give you a little background about how we find the compositions of planet atmospheres. [showing a close-up of a planet transit] As the planet passes in front of the star, it blocks some of the light. If the planet has an atmosphere, then the atmosphere is translucent and actually absorbs much more strongly at the wavelength where the atoms and molecules in the atmosphere absorb. This is core astrophysics! If we observe something as a function of colour, we can see how the different colours of light behave and that [enables] us to interrogate the chemistry of the

material we are [seeing, a] technique is called 'Transmission Spectroscopy'. You look at how deep the transit is as a function of a precise wavelength of the light. That [makes it possible for] you to learn which chemicals are present in the atmosphere of the transiting planet. This is the power of the fantastic telescopes that we have to play with.

A measurement in the ultraviolet by the Hubble Space Telescope, of the first known transiting planet, [shows what you see] if you look at the special colour: [it] tells you about hydrogen. The transit is actually 15% deep, because the planet is surrounded by an enormous cloud of hydrogen. [Now,] 15% is quite easy to measure and that made me think, "You know what! This is just all too exciting!" You really can measure things and get some reliable results. So I abandoned black holes and moved to exoplanets.

These mass-losing planets are in very close orbits; the material is dispersed over quite a large-scale height, which gives you a big lever arm to start doing the differential measurements to detect which colours are being absorbed and learn the chemistry. So, these are good objects for learning the compositions of planets outside our own Solar System. In fact, if you have a mass-losing planet it turns out that [the lost] material can form a cloud of gas that surrounds the star, [engulfing both] the planet *and* the star.

[Another image done] for a press release a few years ago [shows] an image of the Sun during a total [solar] eclipse. [It shows] an outer ring of light, showing you directly the outer layers of the Sun — [the] part of the Sun's atmosphere called the chromosphere, which is hotter than the deeper layers and emits strongly in particular wavelengths. On the right-hand side [of this image] is a spectrum of the host star of WASP-12. *That* spectrum goes down to zero at two points at the bottom of [a] sort of 'W' shape. Also plotted in blue and green [in the image] are three stars [that] behave in the way we expect stars to behave. You can see that they peak up in the 'W'[shape. [These are the chromospheres of those stars, producing light at those particular wavelengths in the same way that the Sun does. WASP-12 does not have that light and the reason is because it is surrounded by a gas cloud, which is absorbing [the light]. So the star is perfectly normal, but it [has] a mass-losing planet [that] is affecting how its starlight looks to us, because it has formed a shroud of gas. So we are [seeing] this particular star [through a veil of gas].

[All these observations and measurements] mean that we can actually pick out the stars that have mass-losing planets. [Showing similar data] on a graph, the Y-axis [shows] how strong that perky little bit at the centre of the 'W' shape [is]. For most stars [this point is] fairly high up in [the] graph, [where a] dotted line [shows] the expected minimum for a normal star, and [a] blue triangle is WASP-12, which has the lowest emission of those particular wavelengths at the centre of that 'W' shape of any known star in our Galaxy. If you look at other known hosts of very close and very hot planets, many of them are [similarly] deficient. These are all giant planets, so not interesting to geologists.

However, if we look very carefully [— as] PhD student Dan Staab [and I did — we have] tidied up the graph and you can see now that there are not many stars below that [dotted] line [for normal, as mentioned above]. [We] hypothesised that those blue points below the line [represent] the host stars of mass-losing hot planets [that have not yet been found]. [We are] using the signatures in the starlight to tell us which stars have these hot, mass-losing planets.

Now, if they [represented] hot Jupiters, we probably would have found them, because hot Jupiters are big and heavy. [But because] these are bright, nearby stars we should have found them. [We figured, therefore, that] these are actually host stars of hot, mass-losing, low mass, probably rocky planets, orbiting stars near our own Sun.

So, we set out to try [to] find them; and we think that those systems might include nearby objects, like the [exoplanet described above that has] the dust cloud forming around it. So we went to the observatory in Chile, made a lot of observations, and did careful data analysis. We were [measuring] the motion of the star at a speed not much faster than walking speed. [And] we *have* found planets. In fact, every time we have collected enough data, we have found planets, just as we thought we would from the [signatures] in the starlight.

The data for our first planetary system, a system of four or five low-mass planets — found so far — with orbits between two and 24 days, includes at least three 'super-Earth' planets (planets with masses less than about 10 Earth masses) that [they] must have some mass loss going on to produce [the] signature in the starlight [shown in the data]. So, we think that we [probably have] rocky planets; we think that the system is viewed edge-on, because [the] gas cloud should be in the orbital plane as transits are likely. Putting [together] everything we know about this [system], we should be able to measure the masses, radii and composition relationships for [the planets in the] system. And we [have] about another 40 still to do! I think this is going to be a really interesting start for doing 'exogeology'.

[Conclusion]

[The data I have presented in this article are] what we knew in 2016 about the mass-radius relationships of the planets and what you can see is that most of [our] measurements have large uncertainty ranges. In fact, pretty much the only ones that have decent precision measurements are the ones in our own Solar System. We [are reasonably] sure about the masses and sizes of the planets in our own Solar System. And there is one other exoplanet, called 55 Cancri e, that is quite well measured. [So] the systems that we are [discovering] will revolutionise this graph by adding [many] more well constrained points [to it]. Furthermore, our systems [make it possible for] us to directly sample the materials [that] those planets are made of.

[To conclude, here] is something that I [recently] came across on the Web. [The title is:] "Highly volcanic exoplanets; lava worlds and magma ocean worlds; an emerging class of dynamic exoplanets of significant scientific priority". [So, I am not the only astronomer reaching these conclusions.] This [Web article] is a consensus of people who are submitting a white paper to advise the United States [of America] on the next decade's scientific priorities. [The ideas and research that I have] introduced in this article [are work] recognised as being an exciting area of science for the next 10 to 20 years or so. The nice thing about it, [is that it] has rich opportunities for an interplay between astrophysics and geology, so I hope that some of you who are studying geology here at the OU might be tempted to move into the exoplanets field and maybe apply what you know about geology to these exciting worlds outside our own Solar System. The Open University [itself] is well positioned [to move this research forward having found] some particularly informative exoplanets.

The 'spinning-top' Asteroids Bennu and Ryugu

Ben Rozitis

The Open University

Introduction

Asteroids are the left-over building blocks that formed the planets in the Solar System 4.5 billion years ago. They are essentially the rocks that failed to fully coalesce together to form planets when the initial solar nebula (i.e. a very large cloud of dust and gas) collapsed under its own gravity to form the Sun and the eight planets. Therefore, asteroids are very interesting bodies for scientists to study because they retain information on the types of material that formed the inner rocky terrestrial planets and the outer gas giant planets. They can also inform us about a number of physical and evolutionary processes that have happened within the Solar System since its birth. For instance, it is now believed that asteroids were the dominant source of water and organics that were delivered to the Earth via impacts shortly after it formed, and so by studying asteroids we can potentially learn how life arose on Earth too.

Since the discovery of the first asteroid in 1801, we have now discovered more than half a million asteroids, and we are continually discovering new ones at a rate of a few tens per day from modern all-sky astronomical surveys. They range in size from a few metres across up to a 1000km in diameter (n.b. the largest and first discovered asteroid — (1) Ceres — was re-classified as a dwarf planet in 2006 due to its large spherical shape). Most asteroids are found in the 'main asteroid belt' between the orbits of Mars and Jupiter, but *c.* 20,000 asteroids are on Earth-crossing orbits. Of these so-called 'near-Earth asteroids', *c.* 2,000 are considered to be 'potentially hazardous' because they have a non-zero chance of impacting the Earth over the next two centuries, and have the potential to cause significant levels of damage if they do impact. As these near-Earth asteroids are on orbits similar to Earth's orbit — especially potentially hazardous ones — they are actually rather easy targets for a spacecraft to get to in terms of fuel needed and/or size of rocket. Therefore, they have recently become attractive targets for planetary space missions, and there are two missions that are currently attempting to return samples from two different near-Earth asteroids: NASA's OSIRIS-REx mission to (101955) Bennu, and JAXA's Hayabusa2 mission to (162173) Ryugu (Fig. 1). Both missions arrived at their target asteroids in 2018 and will return their collected samples to Earth by 2023.

NASA/Goddard/University of Arizona via AP
Supplied: JAXA, University of Tokyo, Kochi University, Rikkyo University, Nagoya University, Chiba Institute of Technology, Meiji University, Aizu University, AIST

Figure 1 The asteroids (101955) Bennu (left) and (162173) Ryugu (right), which are the targets of NASA's OSIRIS-REx and JAXA's Hayabusa2 missions, respectively (image credit NASA and JAXA).

Asteroid sample-return

Why do we need asteroid sample-return? Especially when we already have a very large meteorite collection on Earth (i.e. meteorites are chunks of asteroid that have naturally fallen to Earth)? First of all, there is a huge benefit in studying rock samples in the laboratory, regardless of whether they are from a meteorite or returned by a spacecraft, because it enables us to make detailed quantifications of their chemical and isotopic compositions. Generally, such levels of characterisation are not possible by other remote sensing means, and these data thereby provide additional insights into the various stages of planetary formation. These insights range from the nuclear synthesis that occurred in the early stars that exploded to form the solar nebula, to chemical processes that occurred when the dust and gas cloud of the solar nebula collapsed under its own gravity, and to various alteration processes that occurred when the Solar System's initial planetary bodies collided.

The two disadvantages with studying meteorites are that they are not as pristine as asteroids, and for many of them it is uncertain as to exactly which asteroid they came from. Meteorites have to survive entering the Earth's atmosphere, which subjects them to huge amounts of heating, and then they could be left on the ground for many years before being discovered for study. Therefore, they are subject to terrestrial contamination, which makes studying some planetary formation processes, such as thermal and aqueous alteration, very difficult. Spacecraft sample-return simply skips atmospheric entry and prevents terrestrial contamination, to give us a pristine sample for laboratory analysis.

The other advantage with spacecraft sample-return is that we know exactly which asteroid the sample came from. Furthermore, we can purposefully choose the spacecraft target asteroid to fill in gaps in our knowledge of the meteorite collection. For many meteorites, we have a good idea as to where they came from by comparing their laboratory reflectance spectra to telescopic observations of asteroids. However, for many other meteorites there are no clear links to their parent asteroids. This could be because their reflectance spectra are ambiguous, their parent asteroid does not exist anymore, and/or perhaps they are from an internal part of an asteroid that cannot be seen with a telescope. Therefore, by having a sample returned from a carefully chosen target, we can unlock the many secrets hidden within our existing meteorite collection. We can potentially add missing material to this collection by also returning material that might not necessarily survive atmospheric entry.

OSIRIS-REx and Hayabusa2

To address the need of asteroid sample-return, NASA and JAXA have implemented the OSIRIS-REx and Hayabusa2 missions,

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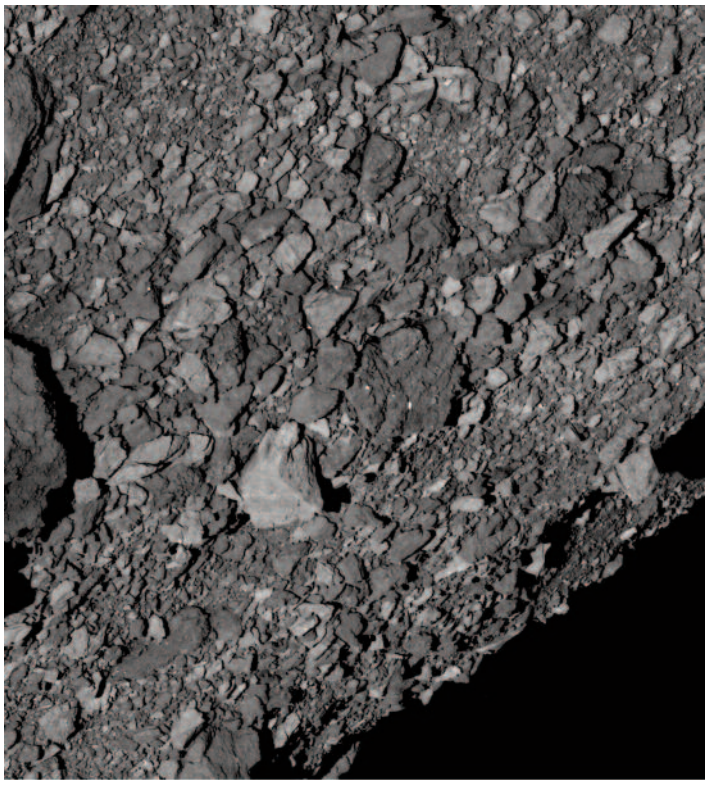
respectively. They follow in the footsteps of three previous near-Earth asteroid missions: NASA's NEAR-Shoemaker mission to (433) Eros in 2000 (i.e. the first spacecraft to orbit an asteroid); JAXA's original Hayabusa mission to (25143) Itokawa in 2005 (i.e. the first attempt at an asteroid sample-return); and China's Chang'e 2 mission to (4179) Toutatis in 2012 (i.e. the first spacecraft to visit an asteroid from lunar orbit). These first three missions provided essential information and experience about how to navigate a spacecraft around an asteroid with very little gravity, and how to map an irregular-shaped body to gain maximum science return. As such, OSIRIS-REx and Hayabusa2 carry an armoury of navigation devices, mapping instruments and sample collection devices in order to achieve their ambitious goal of returning large quantities of material from the surfaces of their target asteroids. In particular, the >60g of material to be returned by OSIRIS-REx, and the several grams to be returned by Hayabusa2, will be the largest quantities of non-terrestrial material returned to Earth since the lunar Apollo missions in the 1960s and 1970s. Like the Apollo samples, this returned asteroid material will keep laboratory scientists busy for many decades to come. After launching in 2014 (Hayabusa2) and 2016 (OSIRIS-REx), the two spacecraft safely arrived at their target asteroids in 2018 after two-four-year cruises through space.

Asteroids Bennu and Ryugu

The targets of the OSIRIS-REx and Hayabusa2 missions are the near-Earth asteroids (101955) Bennu and (162173) Ryugu, respectively. They were chosen because of their B- and C-type spectral types, which are carbonaceous in nature and are strongly suspected to be linked to the CM-type meteorites that have fallen to Earth. As such, they are believed to be made up of some of the most primitive material that was left over from the formation of the Solar System 4.5 billion years ago. They also share similar orbits to that of the Earth, which means that they were relatively easy targets for a spacecraft to get to.



After arriving in 2018, OSIRIS-REx and Hayabusa2 found Bennu and Ryugu to be surprisingly similar in terms of size, shape and surface morphology. In particular, Bennu and Ryugu are *c.* 500m and 900m in diameter, respectively, and share a distinctive 'spinning-top' shape. Both have been found to have surfaces dominated by many boulders larger than a metre in size (Fig. 2). Such a boulder-dominated surface is rather worrisome for a sample-return mission because it implies a lack of suitable-sized material for sample collection, and the large boulders present a navigation hazard to the spacecraft themselves. Nevertheless, both missions pressed on, and the spacecraft engineers and scientists found workarounds to counter the hostile surfaces found at Bennu and Ryugu.

During its encounter, Hayabusa2 dropped three 'hopping' mini-rovers, a larger lander and an explosive crater-making projectile onto the surface of Ryugu. As a result, it returned the first images from the surface of an asteroid (Fig. 3, *opposite*), which highlighted Ryugu's extremely rugged terrain full of boulders. It made two sample collection attempts in February and July 2019, and departed the asteroid in November 2019. We will not know what quantity of material is collected until its sample capsule is returned to Earth in December 2020.

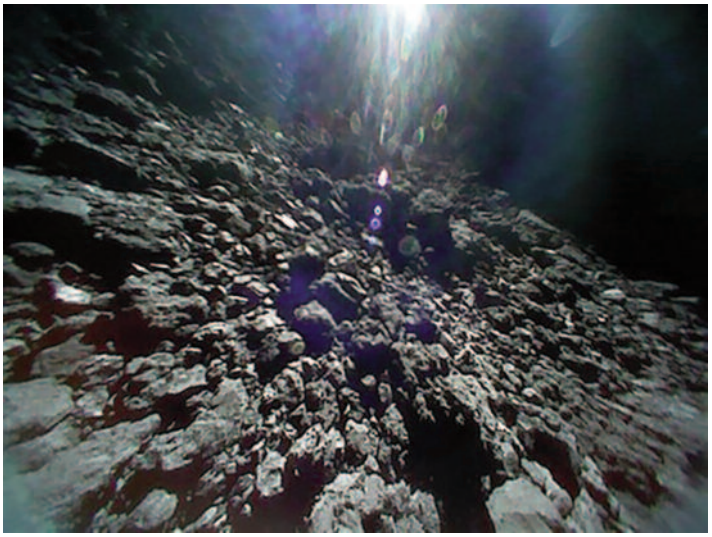
On the other hand, OSIRIS-REx has spent more than a year mapping Bennu in order to find the most suitable sample sites. In December 2019, NASA announced the two chosen sample sites that OSIRIS-REx will attempt to sample in August 2020. During this mapping campaign, OSIRIS-REx made the surprising discovery that Bennu was explosively ejecting particles from its surface. It is believed that these particle-ejection events are either caused by Bennu's boulders undergoing thermal fracture owing to day–night temperature cycles, and/or by micrometeorite impacts onto Bennu. Regardless of the cause, these particle-ejection events should give rise to a Bennu meteor stream that is observable in late September.

Origin of 'spinning-top' shapes

The 'spinning-top' shapes of Bennu and Ryugu are a curious feature of them both, but can be explained by their internal structure and the non-gravitational forces that act on asteroids. For instance, OSIRIS-REx and Hayabusa2 have determined that both Bennu and Ryugu have low densities (i.e. relative to solid rock values) implying that *c.* 50% of each of their internal volumes is actually empty space. Such low densities mean that these asteroids are 'rubble-piles', and are essentially just collections of rocks loosely held together by their own gravity. This, therefore, means that their shapes are rather malleable by external forces, and in this case it is sunlight that causes them to form a 'spinning-top' shape. In particular, the momentum carried by photons of sunlight can impart a net torque on an irregularly-shaped asteroid, which can cause them to spin faster or slower over time, depending on the shape of the asteroid. This process is known as the Yarkovsky-O'Keefe-Radzievskii-Paddack or YORP effect. If the YORP effect continually spins-up an asteroid then it will reach a point where the rotational centrifugal force can balance or exceed the asteroid's self-gravity. It is at this point that the asteroid's shape will start to deform, and it generally deforms into a

Figure 2 The boulder dominated surface of asteroid (101955) Bennu as imaged by OSIRIS-REx. The large and light-coloured boulder just below the centre of the image is c. *7.4m wide (image credit NASA).*

'spinning-top' shape like that of Bennu and Ryugu. Such 'spinning-top' shapes are not unusual, as radar observations conducted by the Arecibo radio telescope have revealed that *c.* 16% of all near-Earth asteroids have this characteristic shape.



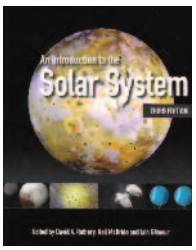
Future asteroid research

Hayabusa2 is now making its return journey to Earth, and will drop off its sample-return capsule at Australia's Woomera Test Range in December 2020. OSIRIS-REx still needs to make its sample collection attempts in August 2020, and if successful then it will have to remain at Bennu for another year before it can start its return journey to Earth. After departing Bennu, OSIRIS-REx will eventually return to Earth in September 2023, where its sample-return capsule will be dropped off at the US Air Force's Utah Test and Training Range. When the samples from both missions are back on Earth, they will be carefully curated and distributed to laboratories around the world to begin the next phase of scientific endeavour for these two missions — to understand Bennu and Ryugu at the microscopic level in context with the meteorite collection. The returned samples will likely answer many questions about our Solar System, but they will inevitably raise new ones as well! As such, large proportions of the returned samples will also be kept in clean storage for future generations of scientists and laboratory equipment to study.

Figure 3 The surface of asteroid (162173) Ryugu as imaged by one of Hayabusa2's hopping rovers (image credit JAXA).

Book review

Rothery, David A., McBride, Neil, Gilmour, Iain (eds) 2018 *An Introduction to the Solar System* (3rd edn). Cambridge UP/The Open University. (ISBN 978-1-0843084-5; 440pp; paperback £44.99)



This book is part of the 30-point Open University course 'S283: Planetary science and the search for life'. I hesitated before agreeing to review this publication, as I did not want to read 'just another book' that systematically described the Solar System, starting with the Sun and running through each of the planets in turn. I am pleased to say this was not such a book.

Although we start with a quick run through of the planets, we are, from Chapter 2, tackling issues such as volcanism, atmospheric composition and impact cratering. Throughout the book the emphasis is on explaining the science that underpins our knowledge of the formation of the Solar System and the planets. The physics and chemistry are second-level and the concepts learned will aid understanding of some terrestrial geological processes.

The book is organised in a standard 'Open University' format, with clear text and standard page layout. There are also 328 excellent colour images, detailed appendices of relevant facts and figures in tabular form and a helpful glossary. Questions test your knowledge as you progress through the book, with comprehensive worked-through answers given at the back of the book. Each chapter ends with a summary of the important points covered.

The text and illustrations have been updated to include recent discoveries from exploration missions, including NASA's Juno orbiter in the Jovian system during 2016 and New Horizons flyby of Pluto in 2015 (incorrectly stated as 2016 on page 274 — a rare lapse). The website of the Cambridge University Press hosts a limited range of additional resources.

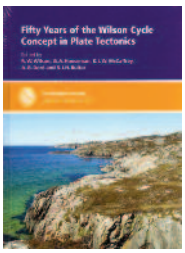
The planets' satellites are referred to occasionally in the text, but not covered in any great detail. It should be noted that there are two volumes supporting the S283 module and the satellites are dealt with more fully in the companion volume: *An Introduction to Astrobiology*. This volume, *An Introduction to the Solar System*, it should be stressed, can still be read as a stand-alone book.

Who is this book aimed at? It is an undergraduate text, but do not let that put you off. The reader is assumed to have limited knowledge of the subject and consequently concepts are well explained. For the earth scientist the chapters on the internal structure of planets, planetary volcanism and meteorites will be of special interest. I struggle to find anything negative to say about the book, but should perhaps mention the price. A quick search of the Internet will find a much more affordable copy; just ensure that you purchase the 3rd Edition for what is a rapidly evolving branch of science.

— Geoff Downer, BA (Hons) (Open)

Book review

Wilson, R. W., Houseman, G. A., McCaffrey, K. J. W., Doré, A. G., Buiter, S. J. H. (eds) 2019 *Fifty Years of the Wilson Cycle Concept in Plate Tectonics*. London: Geological Society, Geol Soc Spec Publ 470. (ISBN 978-1-78620-383-0; 490pp; hardback £140.00)



'Fifty Years of the Wilson Cycle Concept in Plate Tectonics' is a collection of papers discussing various aspects of the Wilson Cycle in detail. There are 21 papers in all. The overview paper, appearing at the beginning of the volume, gives the reader some background information regarding the Wilson Cycle and explains concepts associated with the cycle. This overview introduces and describes the stages of the Wilson Cycle and mentions the early workers who laid the foundations for Tuzo Wilson's classic work.

The remaining 20 papers are organised into six sections or 'themes' (as they are described in the introductory paper).

The themes are: 'The Classic Wilson v. Supercontinent Cycle'; 'Mantle Dynamics in the Wilson Cycle'; 'Tectonic Inheritance in the Lithosphere'; 'Revisiting Tuzo's question on the Atlantic'; 'Opening and Closing of Oceans' and 'Cratonic Basins and their place in the Wilson Cycle'. As is noted in the overview, some papers overlap several themes.

Each section contains a different number of papers. The sections with the greatest number of papers are 'Tectonic Inheritance in the Lithosphere' (five papers) and 'Revisiting Tuzo's question on the Atlantic' (six papers), so these areas are covered in the greatest depth with papers ranging from relatively short and uncomplicated overviews of the subject to much longer and more detailed discussions of the question under review. At the other end of the scale, both 'Mantle Dynamics in the Wilson Cycle' and 'Cratonic Basins and their place in the Wilson Cycle' contain only one paper each. Common to each section is that the papers are, on the whole, presented in an order in which concepts introduced and explained in one paper are built on and discussed in greater depth in a subsequent paper. The exception is the order in which the papers by Şengőr *et al.* and by Heron *et al.* appear in the Tectonic Inheritance in the Lithosphere' section. The order of these two papers could usefully have been reversed. Heron *et al.* introduce several concepts that are more fully discussed in the paper by Şengőr *et al.* It could be helpful to read these papers in reverse order if the reader is not familiar with the subject matter.

Each paper in the collection contains relevant diagrams, in colour and in black and white, and tables where necessary. There is a very useful colour pull-out map of the Appalachian-Caledonian orogen in North America, Ireland and Britain. In occasional papers, the number and density of diagrams makes it difficult to follow the flow of text.

The book has 490 pages and is a good quality hardback, with semi-glossy pages that will stand up to having notes pencilled lightly on them. There is a well laid out contents page, a full reference list at the end of each paper and a comprehensive index at the back of the book. It was, however, surprising to find several spelling and typographical errors in a book of this quality. While this book may appeal to the general reader with a deep interest in the Wilson Cycle, it is more likely to find a greater readership in those who are studying and/or researching the subject.

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Volatiles in the inner Solar System

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Abstract

Volatile elements are key to many processes that operate in our Solar System. Recent *in situ* measurements of volatiles (H_2O, Cl and F), particularly in lunar and martian samples, have changed our understanding of the volatile inventory of the inner Solar System. While this research has provided a wealth of data for these planetary bodies, currently little is known about the history of volatiles in other bodies in the inner Solar System.

Meteorites provide a window into the history of the Solar System and are key to understanding its formation and evolution. The majority of these samples come from a variety of small parent bodies (asteroids), while a small fraction originates from larger bodies such as the Moon and Mars. The variety of meteorites, both in terms of composition and age, enables us to study different parts of the Solar System, as well as different points in its evolution. The Howardite-Eucrite-Diogenite (HED) suite of meteorites represents the largest suite of crustal rocks available from a differentiated basaltic asteroid and accounts for between 2% and 3% of all meteorites collected globally. This group of meteorites is also some of the oldest igneous rocks in the Solar System, and the rocks have remained relatively unaltered since their formation *c.* 8Ma–20Ma after the formation of the Solar System. They offer insight into the planetary accretion process(es).

By investigating the abundance and source(s) of volatiles in the HEDs we can begin to constrain the timing of when water (H_2O) existed in the inner Solar System. Knowing precisely when water accreted in the inner Solar System also has implications for how and when life emerged on Earth and possibly beyond.

Introduction

Volatile elements play a fundamental role in planetary formation and evolution through their influence on a number of processes. These are a group of elements or compounds with low boiling points and some of the last elements to condense out of the solar nebula (Lodders 2003). The abundance of these elements can affect the viscosity of a melt, the explosivity of eruptions such as those seen on Mercury (Thomas *et al.* 2014), as well as the type of minerals that can form (e.g. Filiberto and Treiman 2009; Filiberto *et al.* 2012). They are also a key ingredient for life as we know it. Some of the main questions we can begin to understand and solve through the analysis of volatiles are:

- What are the sources of water and other volatiles in the inner Solar System?
- What is the timing of volatile accretion?
- Was the inner Solar System dry or wet?

We can begin to address all these questions through the study of meteorites. Meteorites provide a window into the history of the Solar System and are key to understanding its formation and evolution. The majority of these samples come from a variety of small parent bodies (asteroids), while a small fraction originates from larger bodies such as the Moon or Mars. The variety of meteorites, both in terms of composition and age, enables us to study different parts of the Solar System as well as different points in its evolution.

Meteorites can be broadly separated into differentiated achondrites and undifferentiated chondrites, the latter typically contain chondrules, coalesced spherical dust aggregates that were subsequently rapidly melted and cooled (e.g. Grady and Wright 2006; Connelly *et al.* 2012; Grady *et al.* 2014). Following their formation, chondrites remain unmelted and have compositions close to that of the solar photosphere in all but the most volatile of elements (Hutchison 2004). Further sub-division of chondrites is based on mineralogy, mineral composition and textural characteristics (Weisberg *et al.* 2006), as well as oxygen isotope composition (Clayton *et al.* 1976; Clayton and Mayeda 1996).

Achondrites are igneous rocks (melts, partial melts, melt residues) or breccias of igneous rock fragments, from differentiated asteroids and planetary bodies (e.g. Mars, Moon). These meteorites provide us with an analogue for early planetary differentiation and evolution, one that can be split into several steps based on the size of the body concerned. Meteorites from asteroids such as 4 Vesta and the Angrite parent body provide insights into processes operating in relatively small planetary bodies. In contrast, meteorites from large planets such as Mars, which displays no current sign of plate tectonics or geological activity (e.g. Sleep 1994; Lenardic *et al.* 2004), provide insights into processes and their products in bodies that are comparable to Earth-like analogues. Crucial to the formation and evolution of differentiated bodies is the presence of, delivery to and behaviour of volatiles on the parent body.

In this work the origin, abundance, distribution and isotopic composition of water (measured as either H_2O, OH, or H, but for the purposes of this work all measurements have been converted into their H_2O equivalent) is explored for the inner Solar System.

Bulk measurements of volatiles

Measurements of the bulk water content in meteorites indicates a positive correlation between abundance and heliocentric distance (Morbidelli *et al.* 2012) (Fig. 1. *overleaf*). The samples that are believed to have formed closest to the Sun are the enstatite chondrites, which are linked to the E-type asteroids (Clark *et al.* 2004). As their name suggests, these samples are rich in the magnesium end member of pyroxene enstatite. Samples from this group range in bulk water content from 0.05wt% to 0.2wt% H_2O content (Hutson and Ruzicka 2000) (where 1wt% equals 10,000ppm). Next the ordinary chondrites, which make up *c.* 87% of meteorite finds, are linked to S-type asteroids and have a more consistent abundance of *c.* 0.1wt% H_2O (Robert *et al.* 1977). Farther out, at or near the snow-line (the distance at which it is cold enough for water ice to condense in the early Solar System) and beyond the carbonaceous chondrites contain significant amounts of water — up to 10wt% H_2O (Kerridge 1985).

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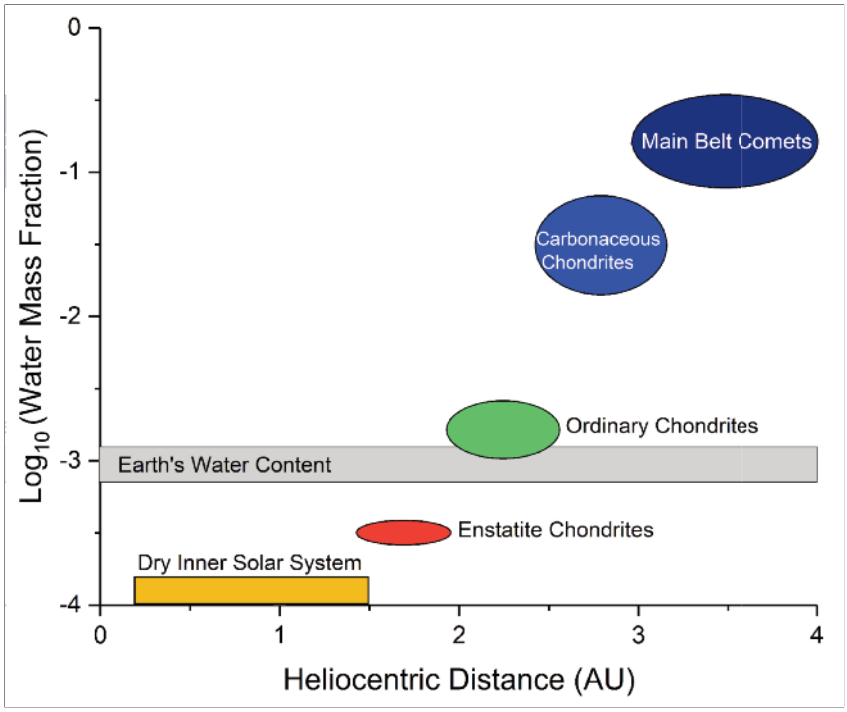


Figure 1 Depiction of bulk water mass fraction vs heliocentric distance for asteroid and cometary samples (redrawn and modified after Morbidelli et al. *2012, fig. 5).*

As the Hayabusa 2 mission target Ryugu shares some similarities with C-type asteroids, we would expect high water content from the samples that will be returned in late 2020. Earth, however, has a much higher water content than we would expect for its heliocentric distance. One possible solution for this is the later delivery of volatiles to the Earth after it had formed by water-rich meteorites and comets. Theoretical models such as the Grand Tack (Walsh *et al.* 2011; O'Brien *et al.* 2014) and the Nice Model (e.g. Tsiganis *et al.* 2005) provide methods for scattering water-rich material from the outer Solar System into the dry inner Solar System. To test this delivery mechanism we need to investigate meteorite samples that would have been around during this time period.

One group of achondrites stands out as a good candidate for evaluating and assessing the history of volatiles in the inner Solar System, defined as the terrestrial planets and the asteroid belt: the Howardite-Eucrite-Diogenite (HED) meteorites. The HED group of meteorites comprise the largest suite of crustal and sub-crustal igneous rocks available from a differentiated basaltic asteroid, and have a strong link to a parent body, namely 4 Vesta located in the inner part of the asteroid belt (McSween *et al.* 2012). Since HED meteorites are some of the oldest achondrites, typically with crystallisation ages from 4,547Ma to 4,559Ma (Misawa *et al.* 2005; Zhou *et al.* 2013), determining their water inventory can provide crucial insights into the processes involved in the early water delivery to the inner Solar System.

In situ measurements of volatiles

While bulk measurements can provide some insight into the volatile abundance of a sample, such measurements lose the geological context that can be crucial to fully understanding the results and their implications. *In situ* measurements target individual mineral phases and keep the overall spatial and geological context intact. Apatite ($Ca_5[PO_4]_3[F, Cl, OH]$) is a widely distributed accessory phase in planetary materials, and it contains fluorine, chorine and water (as OH-) as part of its crystal structure. Because of this, apatite has been used as a recorder of volatiles in magmas and magmatic source regions (e.g. Sarafian *et al.* 2013; Barnes *et al.* 2014; McCubbin *et al.* 2014; Barrett *et al*. 2016). As apatite is the most common volatile bearing mineral in both eucrite and lunar samples, and its affinity for volatiles in its crystal structure it makes data acquisition easier, it is commonly the mineral of interest for volatile studies. Work by Boyce *et al.* (2014), however, showed that care needs to be taken in calculating the parental magma volatile content using apatite data.

Other options for *in situ* analysis include nominally anhydrous minerals (NAMs) and melt inclusions (MIs). NAMs such as pyroxene and plagioclase are some of the main rock-forming minerals and typically much larger than apatite and melt inclusions, making analysis easier. These minerals also have well defined partition coefficients, which means the parent magma's volatile composition can be more easily calculated. NAMs by their nature, however, do not contain a significant amount of water (10s of ppm) and therefore are very susceptible to terrestrial contamination and high instrumental backgrounds. Melt inclusions, on the other hand, can have very high water contents and, owing to their rapid crystallisation directly from the melt, they also represent the primitive parent magma signature. Unfortunately, melt inclusions are incredibly rare and typically very small, making their analysis very challenging.

Once the mineral phase has been selected the volatile abundance and isotopic composition of the phases is analysed typically using Secondary Ion Mass Spectrometry (SIMS). While SIMS is a destructive analysis, as it sputters away a small amount of sample, it has a high spatial resolution (down to 3 × 3µm) and still preserves the surrounding minerals, which provides crucial geological context for each individual measurement.

Hydrogen isotopic composition of meteorites

Hydrogen is the lightest element in the periodic table and the most abundant chemical substance in the universe. It has three naturally occurring isotopes, two of which — hydrogen (^1H) and deuterium (^2H or D) — are stable. Isotope species can be fractionated, either by kinetic processes (associated with incomplete and unidirectional processes such as evaporation and diffusion), or by isotope exchange (equilibrium fractionation, where the isotope distribution changes between different chemical species, but where there is no net change in the isotopic composition of the system) (Hoefs 1987). Owing to the large difference in mass between H and D it is possible for significant fractionation to occur during geological processes such as degassing (e.g. Hoefs 1987; Kendall and Doctor 2003). It is because of this potentially significant fractionation that the hydrogen isotope ratio (D/H ratio) of a sample can be used as a 'fingerprint' for the source(s) of water and any process that may have affected the sample with D/H ratios ranging from the proto-solar nebula (–865‰; Levison *et al.* 2010; Altwegg *et al.* 2015) to the martian atmosphere (+4950±1080‰, Webster *et al.* 2013).

The H isotope composition of a sample is usually given using the standard delta notation (δ) in per mil (‰) whereby:

$$\delta D = (D/H_{(Sample)} / D/H_{(VSMOW)} - 1) * 1000$$

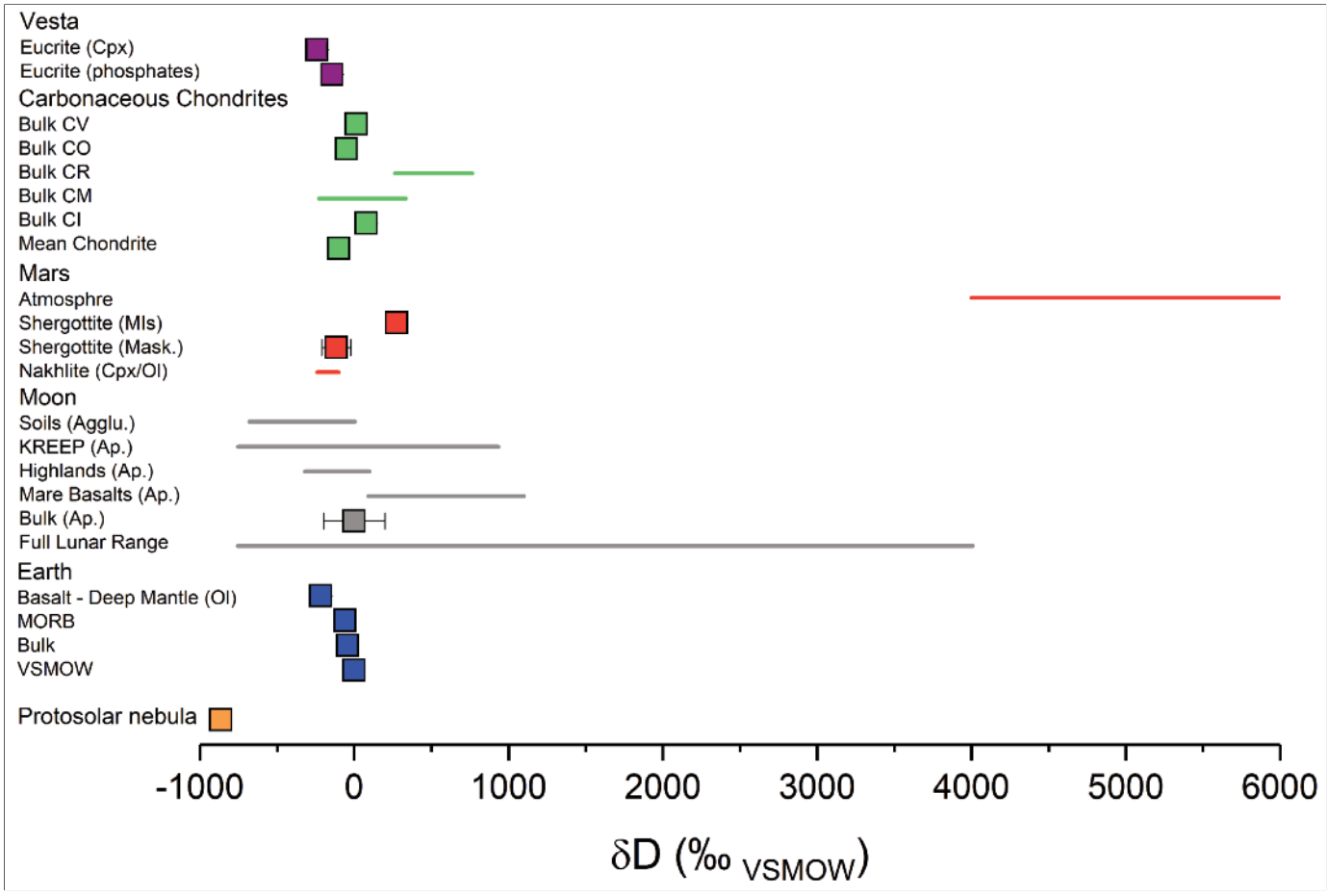
The reference used is Vienna Standard Mean Ocean Water (VSMOW) with a δD value of 0 (Hagemann *et al.* 1970). Lower values indicate relatively more H than D when compared to the standard, whereas higher values indicate the opposite.

Once the data have been acquired, several correction steps are necessary before the data can be properly interpreted. The main correction is for cosmic ray spallation. Spallation is a process caused by the interaction of cosmic rays with a rock residing within a few metres of the surface of an airless planetary body, which causes an increase of δD values through the spallogenic production of D. In samples with low H_2O contents, therefore, the relative proportion of spallogenic D to indigenous D can significantly shift results towards high δD values. Effects of this process on δD values can be corrected by using the cosmic ray exposure (CRE) ages of the studied samples and the production rates of spallogenic H and D (Merlivat *et al.* 1976; Füri *et al.* 2017).

The hydrogen isotopic composition of the Moon is extremely variable, from near proto-solar values (−754‰; Robinson *et al.* 2016) to significantly enriched (*c.* 4000‰; Barnes *et al.* 2014) (Fig. 2). A large portion of these results, however, appear to have a similar isotopic composition to the carbonaceous chondrites (*c.* −100‰; Alexander *et al.* 2012). Magmatic degassing of hydrogen, whereby the lighter isotope H is preferentially lost compared to D, which has the effect of lowering H_2O content and raising the δD value of the sample, has been suggested as the cause for the high values. The low values, however, are harder to explain. Incorporation of solar wind (96% of which is H) has been used to explain low δD values in some lunar samples (Treiman *et al.* 2016); however, Robinson *et al.* (2016) argue against this process and attribute the values to multiple hydrogen reservoirs within the Moon. The water content for the bulk silicate Moon has been estimated by combining data from apatite, NAMs, and melt inclusions. These data provide a relatively wide range of possible H_2O abundances in the bulk silicate Moon from 3–84ppm (McCubbin *et al.* 2015; Ni *et al.* 2019).

Mars's interior H-isotopic composition is currently very poorly constrained due to the large ranges in D/H ratios of phases within the martian meteorites, the range in isotopic composition of martian surface materials, and the presence of at least three distinct H reservoirs on Mars, including an isotopically light mantle (<275‰; Usui *et al.* 2012), isotopically intermediate crust (*c.*1000–2000‰; Usui *et al.* 2015) and the heavy atmosphere (>4000‰,; Webster *et al.* 2013) (*see* Fig. 2). The range of δD values for martian meteorites is *c.* −250–6000‰ (Mane *et al.* 2016; McCubbin and Barnes 2019 and references therein), with the high values explained by some studies as indication of martian atmospheric interaction with the meteorite, possibly during the shock event that launched the rock from the surface of Mars (e.g. Boctor *et al.* 2003; Giesting *et al.* 2015; Hallis *et al.* 2017). The martian atmosphere is believed to have a heavy isotopic composition owing to the preferential escape of H over D in the upper martian exosphere. Other studies have estimated the martian mantle at –116±94‰ (Mane *et al.* 2016), which fits neatly

Figure 2 The range of δD values for various bodies within the inner Solar System (data from, graph redrawn and modified from Stephant et al. *in prep). Individual data: Moon (McCubbin and Barnes 2019 and references therein), Mars (Usui* et al. *2012; Mane* et al. *2016), Chondrites (Alexander* et al. *2012), Vesta (Sarafian* et al. *2014; Barrett* et al. *2016; Stephant* et al. *in prep.).*

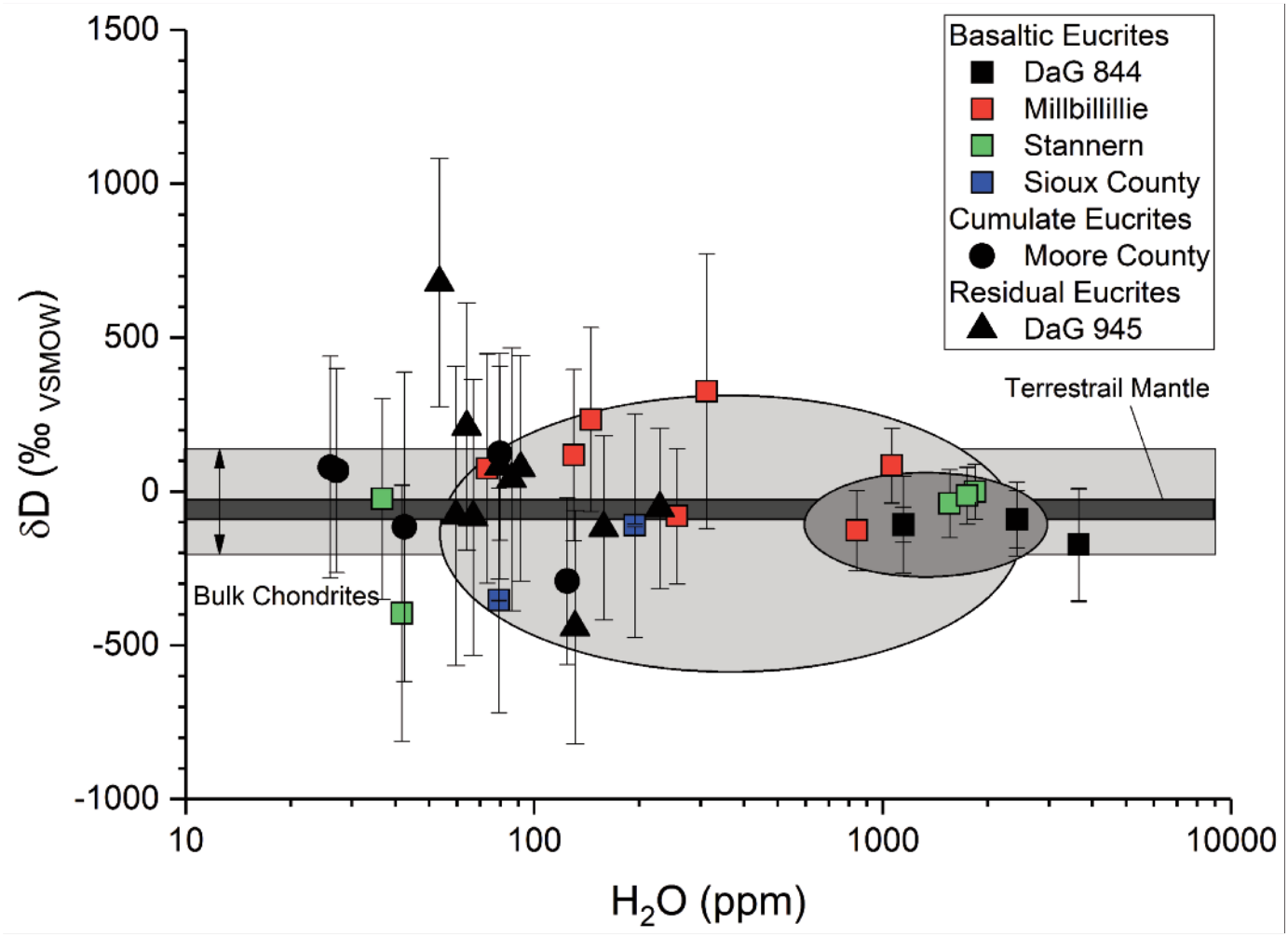


with the possible values for the lunar interior, carbonaceous chondrites and the terrestrial upper mantle. Apatite has been used to estimate the H_2O abundance of the martian interior to range from 83ppm to 321ppm, wetter than the Moon but still a lot less than Earth (700–3000ppm; e.g. Sharp 2017), and this water is believed to be distributed heterogeneously (McCubbin *et al.* 2016; McCubbin and Barnes 2019).

To date, relatively little work has been conducted on determining the volatile content and isotopic composition of HEDs. Sarafian *et al.* (2013) reported on the mineral composition and volatile content of eucritic apatite using electron microprobe analysis of three cumulate eucrites and 10 basaltic eucrites. They followed up their initial work to include in situ isotopic measurements, by SIMS, of H in apatite from some of the same samples (Sarafian *et al.* 2014). Sarafian *et al.* (2014) concluded that, owing to the similarity of H isotopic composition between eucrites and the Earth, and given the ancient ages of eucrites, volatiles could have been added early to the Earth rather than gained during a late accretion event. Although pioneering, the work of Sarafian *et al.* (2013, 2014) was restricted to a small sample set for H isotope analyses and lacked variety in terms of eucrite geochemical and metamorphic grades. With additional investigation of a larger and more representative sample set of available eucrites, Barrett *et al.* (2016) confirmed the striking homogeneity of Vesta, which has weighted average isotopic composition of –151±23‰ (Fig. 3). Preliminary estimates for the bulk Vesta H_2O content were made by Sarafian *et al.* (2019) based on the analysis of NAMs in four samples, which provided estimates ranging from 10ppm to 70ppm, comparable to the lunar interior. More recently Stephant *et al.* (in prep.) greatly expanded upon previous work and obtained the H-isotopic composition of these nominally anhydrous minerals. Their work found that the isotopic composition of eucrite NAMs is lighter than the value observed in phosphates (*see* Fig. 2) (*c.* −250‰, as opposed to *c.* −151‰) and lighter than average carbonaceous chondrite value (–101‰; Alexander *et al.* 2012). This potentially highlights an isotopically lighter reservoir for Vesta than previously expected, which is in line with melt inclusions from Baffin Island, believed to be representative of Earth's primitive mantle (–218‰; Hallis *et al.* 2015).

In their work on the Baffin Island melt inclusions, Hallis *et al.* (2015) observed a negative correlation between δD and H_2O content. They argue that these extreme negative values indicate the existence of a component within the Earth's interior that inherited its D/H ratio directly from the proto-solar nebula. Two methods have currently been proposed for the incorporation of proto-solar hydrogen in what is supposed to be the dry inner

Figure 3 Plot showing δD values versus H_2O contents of apatite from the studied eucrite meteorites. Uncertainties are reported at the 2σ level. The light-grey ellipse represents the field for lunar highland samples (Barnes et al. *2014) and the dark-grey ellipse highlights the range of previously published δD–H_2O data for apatite in eucrites (Sarafian* et al. *2014). The bulk carbonaceous chondrite δD range is derived from Alexander* et al. *2012 and the terrestrial range (−60±20 ‰) taken from Lécuyer* et al. *1998 (figure redrawn and modified from Barrett* et al. *2016).*



Solar System. One is the direct dissolution of H_2 into the Earth's magma ocean as it formed (Sharp 2017); the other is through the chemisorption of hydroxyl (OH) onto forsterite olivine grains, which would enable several ocean masses of water to survive the high temperatures of the early inner Solar System (Asaduzzaman *et al.* 2015). The implications for the inner Solar System are that we could potentially be seeing multiple isotopic reservoirs: one recording a delivery mechanism from the carbonaceous chondrite meteorite group in its late accretion phase, and another more primitive signature that existed since the beginning of planetary formation, possibly accreted from the proto-solar nebula.

Summary and conclusions

Recent analysis of samples from the inner Solar System have provided significant insight into the volatile source(s) and their evolution. Most of the meteorites within our collection give a large range of δD values for their parent bodies, typically ranging several orders of magnitude. Deconvolving all the processes associated with the samples, degassing, solar wind implantation, spallation etc., are not trivial, however, when completed the range of values for much of the inner Solar System (Earth, Moon, Mars and Vesta) are broadly consistent and provide a robust data set for each parent body. More recent investigations have begun to reveal a light, D-poor isotopic reservoir that is potentially prevalent throughout the inner Solar System. This potentially opens up a new and exciting reanalysis of samples as well as an alternate interpretation for the evolution of volatiles within the terrestrial planets.

Acknowledgements

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References

Alexander, C. M. O. D., Bowden, R., Fogel, M. L., Howard, K. T., Herd, C. D. K., and Nittler, L. R. 2012 'The provenances of asteroids, and their contributions to the volatile inventories of the terrestrial planets'. *Science* **337**(6095), 721–23

Altwegg, K., Balsiger, H., Bar-Nun, A., Berthelier, J. J., Bieler, A., Bochsler, P., Briois, C., Calmonte, U., Combi, M., De Keyser, J., Eberhardt, P., Fiethe, B., Fuselier, S., Gasc, S., Gombosi, T. I., Hansen, K. C., Hässig, M., Jäckel, A., Kopp, E., Korth, A., LeRoy, L., Mall, U., Marty, B., Mousis, O., Neefs, E., Owen, T., Rème, H., Rubin, M., Sémon, T., Tzou, C.-Y., Waite, H., and Wurz, P. 2015 '67P/Churyumov-Gerasimenko, a Jupiter family comet with a high D/H ratio'. *Science* **347**(6220), 721–3

Asaduzzaman, A., Muralidharan, K., and Ganguly, J. 2015 'Incorporation of water into olivine during nebular condensation: insights from density functional theory and thermodynamics, and implications for phyllosilicate formation and terrestrial water inventory'. *Meteoritics & Planet Sci* **50**, 578–89

Barnes, J. J., Tartèse, R., Anand, M., McCubbin, F. M., Franchi, I. A., Starkey, N. A., and Russell, S. S. 2014 'The origin of water in the primitive Moon as revealed by the lunar highlands samples'. *Earth Planet Sci Lett* **390**, 244–52

Barrett, T. J., Barnes, J. J., Tartèse, R., Anand, M., Franchi, I. A., Greenwood, R. C., Charlier, B. L. A., and Grady, M. M. 2016 'The abundance and isotopic composition of water in eucrites'. *Meteoritics & Planet Sci* **51**, 1110–24

Boctor, N. Z., Alexander, C. M. O. D., Wang, J., and Hauri, E. 2003 'The sources of water in martian meteorites: clues from hydrogen isotopes'. *Geochim et Cosmochim Acta* **67**, 3971–89

Boyce, J. W., Tomlinson, S. M., McCubbin, F. M., Greenwood, J. P., and Treiman, A. H. 2014 'The lunar apatite paradox'. *Science* **344**(6182), 400–2

Clark, B. E., Bus, S. J., Rivkin, A. S., McConnochie, T., Sanders, J., Shah, S., Hiroi, T., and Shepard, M. 2004 'E-type asteroid spectroscopy and compositional modeling'. *J Geophys Res: Planets* **109**(E2)

Clayton, R. N., Onuma, N., and Mayeda, T. K. 1976 'A classification of meteorites based on oxygen isotopes'. *Earth Planet Sci Lett* **30**, 10–18

Clayton, R. N., and Mayeda, T. K. 1996 'Oxygen isotope studies of achondrites'. *Geochim et Cosmochim Acta* **60**, 1999–2017

Connelly, J. N., Bizzarro, M., Krot, A. N., Nordlund, Å., Wielandt D., and Ivanova, M. A. 2012 'The absolute chronology and thermal processing of solids in the solar protoplanetary disk'. *Science* **338**(6107), 651–5

Filiberto, J. and Treiman, A. H. 2009 'The effect of chlorine on the liquidus of basalt: first results and implications for basalt genesis on Mars and Earth'. *Chem Geol* **263**, 60–8

Filiberto, J., Wood, J., Dasgupta, R., Shimizu, N., Le, L., and Treiman, A. H. 2012 'Effect of fluorine on near-liquidus phase equilibria of an Fe–Mg rich basalt'. *Chem Geol* **312–313**, 118–26

Füri, E., Deloule, E., and Trappitsch, R. 2017 'The production rate of cosmogenic deuterium at the Moon's surface'. *Earth Planet Sci Lett* **474**, 76–82

Giesting, P. A., Schwenzer, S. P., Filiberto, J., Starkey, N. A., Franchi, I. A., Treiman, A. H., Tindle, A. G., and Grady, M. M. 2015 'Igneous and shock processes affecting chassignite amphibole evaluated using chlorine/water partitioning and hydrogen isotopes'. *Meteoritics & Planet Sci* **50**, 433–60

Grady, M. M., and Wright, I. 2006 'Types of extraterrestrial material available for study', *in* Lauretta, D. S., and McSween Jr, H. Y. (eds) *Meteorites and the Early Solar System II*. Tucson: U Arizona P, 3–18

Grady, M. M., Pratesi, G., and Cecchi, V. M. 2014 *Atlas of Meteorites*. Cambridge UP

Hagemann, R., Nief, G., and Roth, E. 1970 'Absolute isotopic scale for deuterium analysis of natural waters: absolute D/H ratio for SMOW1'. *Tellus* **22**, 712–15

Hallis, L. J., Huss, G. R., Nagashima, K., Taylor, G. J., Halldórsson, S. A., Hilton, D. R., Mottl, M. J., and Meech, K. J. 2015 'Evidence for primordial water in Earth's deep mantle'. *Science* **350**(6262), 795–7

Hallis, L. J., Huss, G. R., Nagashima, K., Taylor, G. J., Stöffler, D., Smith, C. L., and Lee, M. R. 2017 'Effects of shock and martian *alteration on Tissint hydrogen isotope ratios and water content'. Geochim et Cosmochim Acta* **200**, 280–94

Hoefs, J. 1987 *Stable Isotope Geochemistry*. Heidelberg: Springer

Hutchison, R. 2004 *Meteorites: A Petrologic, Chemical and Isotopic Synthesis*. Cambridge UP

Hutson ,M. and Ruzicka, A. 2000 'A multi-step model for the origin of E3 (enstatite) chondrites'. *Meteoritics & Planet Sci* **35**, 601–8

Kendall, C., and Doctor, D. 2003 'Stable isotope applications in hydrologic studies'. *Treatise on geochem* **5**, 605

Kerridge, J. F. 1985 'Carbon, hydrogen and nitrogen in carbonaceous *chondrites: abundances and isotopic compositions in bulk samples'. Geochim et Cosmochim Acta* **49**, 1707–14

Lenardic, A., Nimmo, F., and Moresi, L. 2004 'Growth of the hemispheric dichotomy and the cessation of plate tectonics on Mars'. *J Geophys Res: Planets* **109**(E2), E02003

Levison, H. F., Duncan, M. J., Brasser, R., and Kaufmann, D. E. 2010 'Capture of the Sun's Oort Cloud from stars in its birth cluster'. *Science* **329**(5988), 187–90

Lodders, K. 2003 'Solar system abundances and condensation temperatures of the elements'. *Astrophys J* **591**, 1220

Mane, P., Hervig, R., Wadhwa, M., Garvie, L. A. J., Balta, J. B., and McSween, H. Y. 2016 'Hydrogen isotopic composition of the martian mantle inferred from the newest martian meteorite fall, Tissint'. *Meteoritics & Planet Sci* **51**, 2073–91

McCubbin, F. M., Shearer, C. K., Burger, P. V., Hauri, E. H., Wang J., Elardo, S. M., and Papike, J. J. 2014 'Volatile abundances of coexisting merrillite and apatite in the martian meteorite Shergotty: implications for merrillite in hydrous magmas'. *Amer Mineral* **99**, 1347–54

McCubbin, F. M., Vander Kaaden, K. E., Tartèse, R., Klima, R. L., Liu, Y., Mortimer, J., Barnes, J. J., Shearer, C. K., Treiman, A. H., and Lawrence, D. J. 2015 'Magmatic volatiles (H, C, N, F, S, Cl) in the lunar mantle, crust, and regolith: Abundances, distributions, processes, and reservoirs'. *Amer Mineral* (in press)

McCubbin, F. M., Boyce, J. W., Srinivasan, P., Santos, A. R., Elardo, S. M., Filiberto, J., Steele, A., and Shearer, C. K. 2016 'Heterogeneous distribution of H_2O in the martian interior: Implications for the abundance of H_2O in depleted and enriched mantle sources'. *Meteoritics & Planet Sci* **51**, 2036–60

McCubbin, F. M., and Barnes, J. J. 2019 'Origin and abundances of H_2O in the terrestrial planets, Moon, and asteroids'. *Earth Planet Sci Lett* **526**; doi.org/10.1016/j.epsl.2019.115771

McSween, H. Y., Mittlefehldt, D. W., Beck, A. W., Mayne R. G., and McCoy, T. J. 2012 'HED meteorites and their relationship to the geology of Vesta and the Dawn mission', *in* Russel, C. T., and Raymond, C. A. *The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres*. Springer, 141–74

Merlivat, L., Lelu, M., Nief, G., and Roth, E. 1976 'Hydrogen and deuterium in lunar rock 70215'. CEA Centre d'Etudes Nucleaires de Saclay, 91-Gif-sur-Yvette (France). Dept. de Recherche et Analyse

Misawa, K., Yamaguchi, A., and Kaiden, H. 2005 'U-Pb and ^{207}Pb-^{206}Pb ages of zircons from basaltic eucrites: implications for early basaltic volcanism on the eucrite parent body'. *Geochim et Cosmoch Acta* **69**, 5847–61

Morbidelli, A., Lunine, J. I., O'Brien, D. P., Raymond, S. N., and Walsh, K. J. 2012 'Building terrestrial planets'. *Ann Rev Earth Planet Sci* **40**, 251–75

Ni, P., Zhang, Y., Chen, S., and Gagnon, J. 2019 'A melt inclusion study on volatile abundances in the lunar mantle'. *Geochim et Cosmochim Acta* **249**, 17–41

O'Brien, D. P., Walsh, K. J., Morbidelli, A., Raymond, S. N., and Mandell, A. M. 2014 'Water delivery and giant impacts in the 'Grand Tack' scenario'. *Icarus* **239**, 74–84

Robert, F., Merlivat, L., and Javoy, M. 1977 'Water and deuterium content in eight condrites'. *Meteoritics* **12**, 349

Robinson, K. L., Barnes, J. J., Nagashima, K., Thomen, A., Franchi, I. A., Huss, G. R., Anand, M., and Taylor, G. J. 2016 'Water in evolved lunar rocks: evidence for multiple reservoirs'. *Geochim et Cosmochim Acta* **188**, 244–60

Sarafian, A. R., Roden, M. F., and Patiño-Douce, A. E. 2013 'The volatile content of Vesta: clues from apatite in eucrites'. *Meteoritics & Planet Sci* **48**, 2135–54

Sarafian, A. R., Nielsen, S. G., Marschall, H. R., McCubbin, F. M., and Monteleone, B. D. 2014 'Early accretion of water in the inner Solar System from a carbonaceous chondrite–like source'. *Science* **346(**6209), 623–6

Sarafian, A. R., Nielsen, S. G., Marschall, H. R., Gaetani, G. A., Righter, K., and Berger, E. L. 2019 'The water and fluorine content of 4 Vesta'. *Geochim et Cosmochim Acta* **266**, 568–81

Sharp, Z. D. 2017 'Nebular ingassing as a source of volatiles to the terrestrial planets'. *Chem Geol* **448**, 137–50

Sleep, N. H. 1994 'Martian plate tectonics'. *J Geophys Res: Planets* **99**(E3), 5639–55

Stephant, A., Hervig, R., Bose, M., and Wadhwa, M. (in prep.) 'Deuterium-poor water reservoir in the asteroid 4 Vesta and the inner Solar System'

Thomas, R. J., Rothery, D. A., Conway, S. J., and Anand, M. 2014 'Long-lived explosive volcanism on Mercury'. *Geophys Res Lett* **41**, 6084–92

Treiman, A. H., Boyce, J. W., Greenwood, J. P., Eiler, J. M., Gross, J., Guan, Y., Ma, C., and Stolper, E. M. 2016 'D-poor hydrogen in lunar mare basalts assimilated from lunar regolith'. *Amer Mineral* **101**, 1596–603

Tsiganis, K., Gomes, R., Morbidelli, A., and Levison, H. F. 2005 'Origin of the orbital architecture of the giant planets of the Solar System'. *Nature* **435**(7041), 459–61

Usui, T., Alexander, C. M. O. D., Wang, J., Simon, J. I., and Jones, J. H. 2012 'Origin of water and mantle–crust interactions on Mars inferred from hydrogen isotopes and volatile element abundances of olivine-hosted melt inclusions of primitive shergottites'. *Earth Planet Sci Lett* **357–358**, 119–29

Usui, T., Alexander, C. M. O. D., Wang, J., Simon, J. I., and Jones, J. H. 2015 'Meteoritic evidence for a previously unrecognized hydrogen reservoir on Mars'. *Earth Planey Sci Lett* **410**, 140–51

Walsh, K. J., Morbidelli, A., Raymond, S. N., O'Brien, D. P., and Mandell, A. M. 2011 'A low mass for Mars from Jupiter's early gas-driven migration'. *Nature* **475**, 206

Webster, C. R., Mahaffy, P. R., Flesch, G. J., Niles, P. B., Jones, J. H., Leshin, L. A., Atreya, S. K., Stern, J. C., Christensen, L. E., Owen, T., Franz, H., Pepin, R. O., and Steele, A. 2013 'Isotope ratios of H, C, and O in CO_2 and H_2O of the martian atmosphere'. *Science* **341**(6143), 260–3

Weisberg, M. K., McCoy, T. J., and Krot, A. N. 2006 'Systematics and evaluation of meteorite classification', *in* Lauretta, D. S., and McSween Jr, H. Y. (eds) *Meteorites and the Early Solar System II*. Tucson: U Arizona P, 19–52

Zhou, Q., Yin, Q.-Z., Young, E. D., Li, X.-H., Wu, F.-Y., Li, Q.-L., Liu, Y., and Tang, G.-Q. 2013 'SIMS Pb–Pb and U–Pb age determination of eucrite zircons at <5μm scale and the first 50Ma of the thermal history of Vesta'. *Geochim et Cosmochim Acta* **110**, 152–75

Making mountains, on Earth and beyond

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Abstract

Many of Earth's mountains are formed in orogenic belts aligned along plate margins. Their altitudes (reaching >8,000m above sea level in the Himalayas) are the result of the balance between tectonic forces causing their uplift and erosive processes causing their destruction. The tectonic forces result, in part, from isostacy, which is determined by the plasticity of the asthenosphere; but gravity studies across the Himalayas suggest that the highest parts of the range require an additional force to support their altitude, which is provided by the flexural rigidity of the lithosphere. This is well demonstrated by the 2015 earthquake in Nepal, where radar images before and after the 7.8M event record a decrease in altitude of the high Himalayas as a consequence of weakening and rupture of the lithosphere by the earthquake.

Radar images of Venus, a planet of similar size to the Earth, provide evidence of 10,000m mountain ranges, also similar to Earth. However, venusian mountains do not define the sinuous forms of Earth's great ranges. This demonstrates that mountains of Himalayan altitudes can form in the absence of plate tectonics. On Venus, persistent compressive forces acting on hot lithosphere has led to significant horizontal shortening by ductile mechanisms to form fold-and-thrust belts within thickened crust around the margins of crustal plateaux, possibly analogous to tectonics on the early Earth. Maximum altitudes are unlikely to be climate limited (surface erosion on Venus is low due to the absence of water in the atmosphere) and so must be limited by rock strength. The similarity in maximum altitudes of mountains on Earth and Venus suggests that rock strength is probably the dominant factor in determining the maximum height of mountains on both planets.

Mountains are also formed from volcanic eruptions. Comparisons are drawn between Earth's Mauna Kea (10,000m from its ocean-floor base) and the martian Olympus Mons (>21,000m). The staggering dimensions of the latter volcano requires the absence of plate tectonics, which enables a hot spot to generate magmatism at the same point on the surface for hundreds of millions of years. However, the flexural rigidity of the lithosphere must also be sufficient to support the massive volcanic edifice and this is found to be significantly higher on Mars than on the Earth's ocean floor, due in part to the greater thickness of the martian crust and the absence of a low-viscosity asthenosphere. The smaller planetary mass of Mars is also a factor in supporting a volcano of such dimensions.

Extra-terrestrial examples of mountain building are also taken from Saturn's largest moon, Titan, and from the dwarf planet Pluto. Mountains ranges on Titan reach altitudes of *c.* 3,300m, much lower than maximum altitudes on Earth. The mountains are formed in an icy rigid outer layer (surface temperatures are –180ºC), which overlies a water-ammonia sub-surface ocean. On Pluto, with a mass one tenth that of Titan, mountains reach altitudes of *c.* 6,200m. In both cases the low mechanical strength of the sub-surface layer prevents mountains approaching the much greater altitudes of terrestrial mountain ranges and confirms the paramount importance of material strength in determining the heights that mountains can achieve.

"We shall not cease from exploration, and the end of all our exploring will be to arrive where we started and know the place for the first time." — T. S. Eliot

Introduction

This article seeks to review the processes by which mountains can evolve using examples in the inner and outer Solar System. It uses extra-terrestrial examples to identify the forces that fashion Earth's highest mountains and addresses the question 'why are Earth's mountains not higher than they are?'

Tectonic mountain building on Earth

The highest point above on Earth is Mount Everest, which reaches a height of 8,848m above sea level (Fig. 1). We know from the discovery of crinoids (marine fossils) on its summit that Everest has been pushed up from the sea floor, a distance of nearly 9km (Odell 1967). Everest is part of the vast Himalayan mountain chain >2,000km long, which stretches from Pakistan to north-west India, Nepal (where they mark the border with Tibet), Sikkim, Bhutan and into eastern Tibet. These mountains result from the collision between two continental tectonic plates, India and Eurasia, *c.* 50Ma ago. This massive collision continues today as the plates continue to converge due in part to deforming the crust beneath the Himalaya and Tibet. During the deformation both the continental crust and the entire lithosphere are substantially thickened. Uplift follows such thickening through a process called isostacy.

Figure 1 The north face of Mount Everest (8,848m) viewed from the Tibet Plateau.

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To understand isostacy it is useful to consider a series of blocks floating on water (Fig. 2). The more elongated is the block the higher the top of the block will rise above the water's surface. The blocks represent the Himalayan lithosphere, being of lower density than the water (asthenosphere). The tallest blocks have deep lithospheric roots. The base of the block represents the isostatic compensation depth, which is the interface between the bottom of the lithosphere and the top of the asthenosphere. In reality the asthenosphere is not a liquid but a solid that can flow by plastic deformation. Reaching isostatic equilibrium is not an instantaneous process and the time the mountains take to reach their equilibrium altitudes depends on the relative rates of deformation, causing thickening, and of plastic flow in the asthenosphere.

Most mountain ranges are not in perfect isostatic equilibrium. To test for isostatic equilibrium, geophysicists can calculate the gravitational anomaly for theoretical Airy isostatic equilibrium [after George Biddell Airy, 1801–92 — Ed.] at any point across the orogen. In the case of the highest Himalayan mountains the measured gravity anomalies are systematically higher than these equilibrium values (Cattin *et al.* 2001), a situation described as 'under compensation'. Put another way, the topography is not fully supported by the crustal root. This is important because it implies that there is another force supporting the mountains. Incidentally the foreland basin into which the eroded products of the Himalayas are deposited by the Ganges and Brahmaputra rivers is 'over compensated', meaning that the actual crustal root is greater than is predicted by isostatic equilibrium. This is because the rate of deposition of eroded material from the Himalayas (adding mass to the lithosphere at the surface) is faster than flow in the asthenosphere can restore the equilibrium position at that point.

What is this second force supporting the high mountains? A clue to this question is offered by studies of ground movement following the 7.8M Gorkha (Nepal) earthquake in 2015. Radar mapping revealed that while the Kathmandu Valley had risen in altitude, the altitudes of the high Himalayas to the north had actually decreased in height by about 0.6m (Diao *et al.* 2015). The earthquake was the energy released by fault movement, which weakened the lithosphere and so decreased the altitude of mountains that could be supported. The strength of the lithosphere, known as flexural rigidity, is a second key factor in supporting mountains. This rigidity is a function of rock composition, the strain rate and the geotherm.

Any geologist will know that as well as tectonics pushing rocks upwards, there is a potential for surface erosion to reduce altitudes at the surface. There is a balance of upward forces (lithospheric strength and isostacy) pushing rocks upwards (at *c.* 7mm/yr in the central Himalayas), surface denudation (erosion) lowering their elevations (at *c.* 3mm/yr), resulting in a net increase in altitude of *c.* 4mm/yr. There is active debate about whether the limiting factor on mountain elevations is the rate of erosion or the rate of tectonic uplift.

The idea that mountains are carved downwards by their weathering is an old one; in the 19th century a U.S. geomorphologist wrote "the mountains were not thrust up as peaks, but a great block was slowly lifted and from this the mountains were carved by the clouds — patient artists who take what time might be necessary for their work" (Powell 1875). Much more recently it has been noted that most peaks on Earth are *c.* 1,500m above the snowline, and it was concluded that the difference in heights of mountain ranges reflect variations in climate rather than tectonic forces (Egholm *et al.* 2009). To test what is the dominant factor determining mountain elevations it would be useful to find another planet, of similar size to Earth, where tectonics was active but which lacked vigorous erosion.

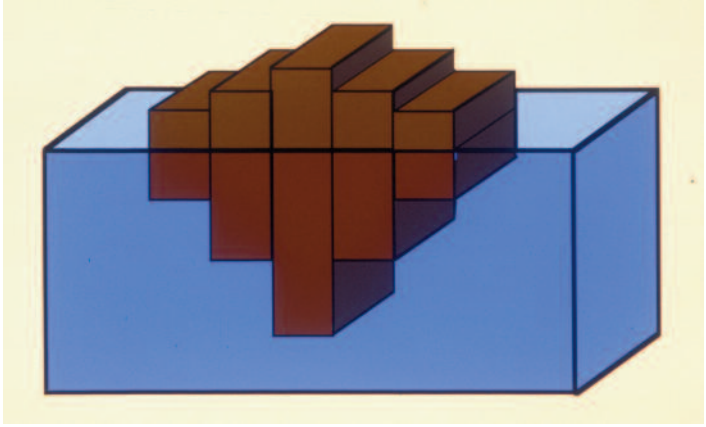
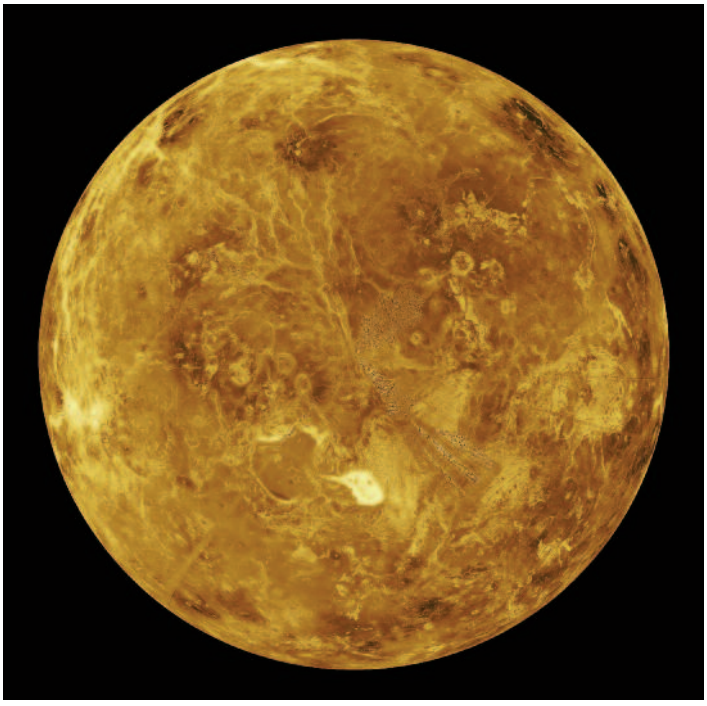


Figure 2 The principal of isostacy illustrated by the analogy of wooden blocks (representing the lithosphere) floating on water (representing the asthenosphere). The highest surface elevations are supported by deep 'roots' protruding into the water. Buoyancy provides the support (© Open University, with permission).

The mountains of Venus

Venus is one of our neighbouring planets with a mass 80% that of the Earth and made up largely of silicate minerals, as is Earth. The atmosphere, though, differs significantly from that on Earth, being composed of CO_2 and sulphuric acid and lacking H_2O. The highest mountain range on Venus is Maxwell Montes, rising to the peak of Skadi Mons at 10,700m (Fig. 3). These altitudes are similar to maximum elevations on Earth, but what differs

Figure 3 Venus, northern hemisphere, compiled from radar images. Maxwell Montes is seen as the white lens in the bottom half of the image (NASA/JPL).



sharply from the Earth is the distribution of the mountains, which tend to develop sub-parallel ridges around high plateau margins (Fig. 3) rather than define linear (Andean) or arc-like (Himalayan) arrays, as on Earth where the major mountain belts have formed along active, or former, plate margins. Seismic studies suggest the crust beneath Maxwell Montes has thickened from 30km beneath the plateaux to 50km beneath the mountains, so topography appears to be supported by a crustal root (Anderson and Smrekar 2006).

Venus is much hotter than Earth — average surface temperatures are 460°C compared to 14°C on Earth. Moreover, the lack of plate tectonics on Venus means that it lacks mid-ocean ridges, features that allow a high proportion of the internal heat loss on Earth. Consequently, the temperature-depth gradient on Venus (the equivalent of the geothermal gradient on Earth) will be much steeper, favouring ductile deformation and the development of mountainous fold-and-thrust belts.

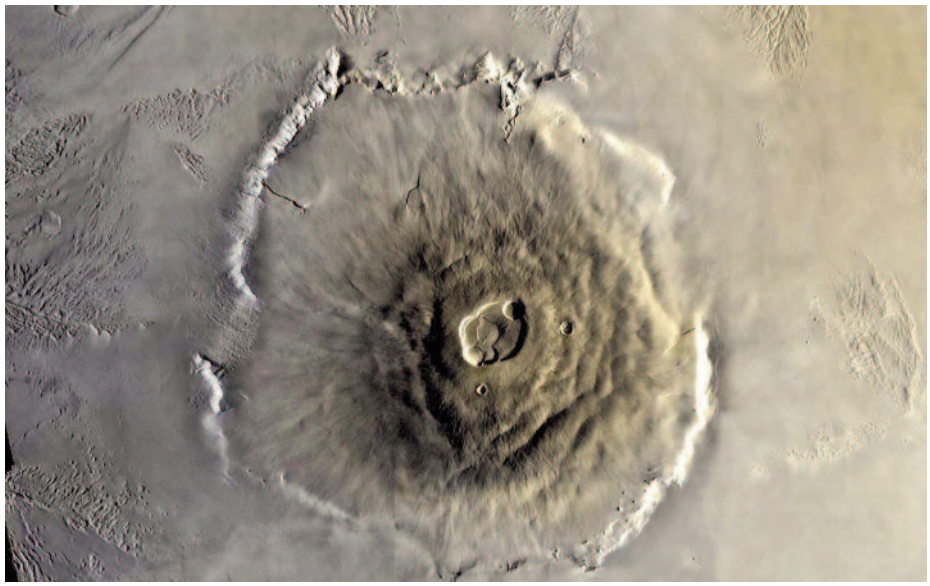


Figure 4 3D image of Mons Olympus (21,229m) on Mars, constructed from colour mosaic (height of image c. *500km — note the flexural moat formed around the perimeter of the structure) (NASA/JPL).*

Comparisons between venusian and terrestrial mountain belts suggest that similar tectonic processes of compression and deformation, with crustal thickening, are at work, albeit Venus offers a one-plate environment. The absence of H_2O in the venusian atmosphere suggests that weathering will be a minor process compared to Earth; indeed the principal causes of erosion of terrestrial rocks, such as glaciers or running water, diurnal and seasonal temperature changes, and aeolian abrasion, are all absent on Venus. The first-order conclusion from this simple comparison is that for silicate planets of mass similar to Earth, tectonics rather than surface erosion largely determines the maximum elevations of mountains.

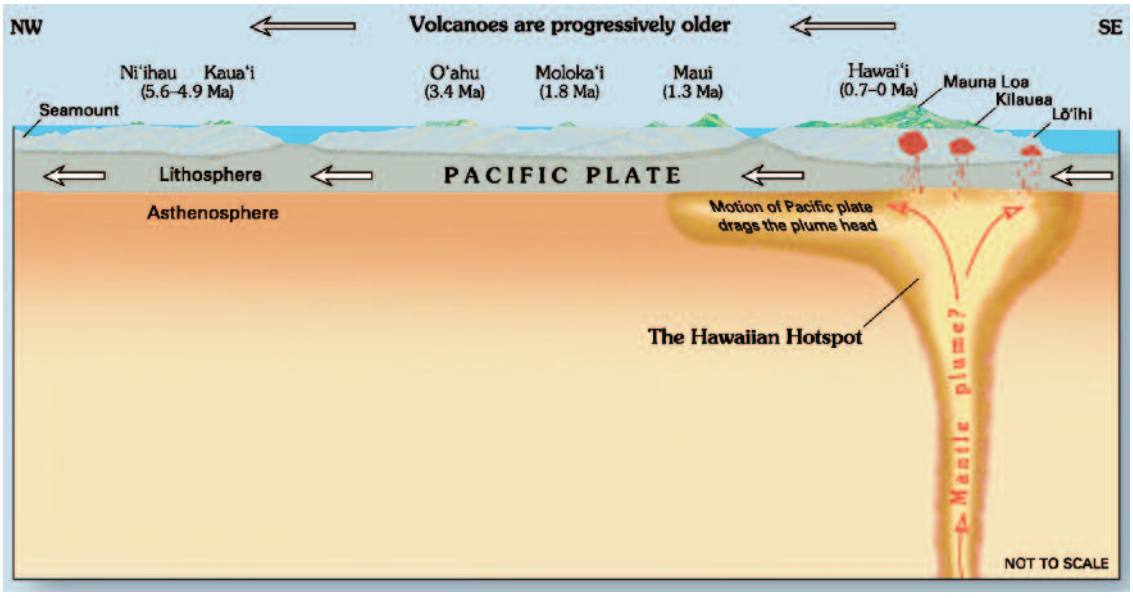
Volcano building on Mars and on Earth

Tectonics provides only one way of constructing mountains. Large mountains can result from repeated volcanic eruptions, which, over time, build up a large carapace typical of most shield volcanoes. Indeed it can be argued that Mauna Kea, one of five volcanoes that make up the Pacific island of Hawai'i, is the highest mountain on Earth. Although only 4,207m above sea level, measured from the sea floor from where the slopes originate, it is 10,200m. Such volcanoes generally grow from seamount summit eruptions, which successively increase the height and width of the volcano; the weight of the growing volcanic pile provides an increasing downward force that is resisted by the flexural rigidity of the supporting lithosphere until the point at which the structure starts to subside.

The largest mountain in the Solar System has such an origin, and is found on our other planetary neighbour, Mars. Olympus Mons rises 21,229m above the martian plains and its base covers the area of France (Fig. 4). How is such an enormous structure possible? Is its existence a function of magma supply or to the strength of the lithosphere?

Olympus Mons eruptions occurred from *c.* 3,670Ma to *c.* 2,540Ma. In comparison eruptions on Hawai'i date back only *c.* 0.7Ma. The calculated eruption rates are similar for the two volcanoes, *c.* 0.01km^3/yr (Isherwood *et al.* 2013). However, a key difference can be seen in the tectonic environment of the two volcanoes. Hawai'i is the prime example of an oceanic hot spot. As the Pacific plate migrates over the hot spot, a chain of islands has formed, tracing the direction of the moving plate (Fig. 5). In contrast, Mars has no plate tectonics and so the hot spot beneath

Figure 5 Diagram of vertical section through the Hawai'i chain forming above the hotspot (Joel E. Robinson, USGS).



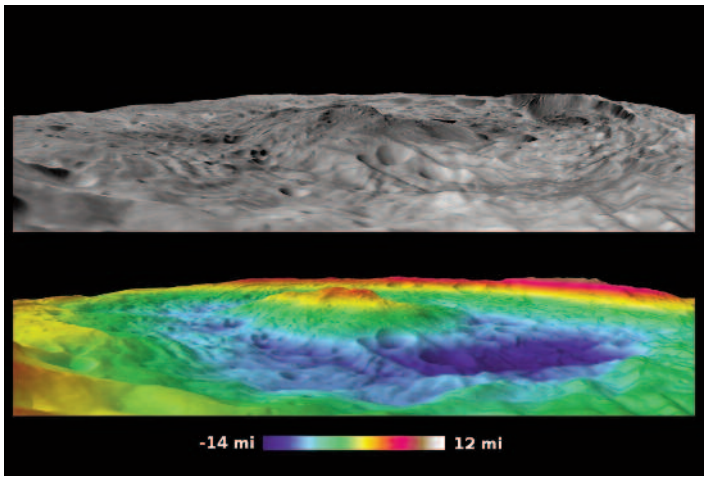


Figure 6 Radar image of south pole of Vesta across the Rheasilvia crater, measuring c. *500km across (scale of false colour in elevation model [below] ranges from depths of 20km [deep blue] to heights of 20km [white]) (NASA/JPL-Caltech).*

Mons Olympus has erupted persistently through the same lithospheric target for the lifetime of the thermal anomaly, in this case over 1,000Ma. So it is not unreasonable to propose that the absence of plate tectonics is a necessary, but not sufficient, condition for the formation of a volcano of the dimensions of Olympus Mons.

A volcano can only increase in altitude if the rocks beneath it are strong enough to support it. Around the base on Mons Olympus a flexural moat can be seen, which is indicative that the great weight of the volcano is close to the limit that can be supported on Mars (*see* Fig. 4). The seismic evidence from Mars suggests that the rocks are indeed stronger than those beneath Hawai'i, whether measured in terms of a greater crustal thickness (140km versus <20km), flexural rigidity (1×10^{32}Nm versus 1×10^{23}Nm) or effective elastic thickness (>70km versus <40km) (McKenzie *et al.* 2002). It seems that both the lack of plate tectonics on Mars and the strength of its rocks contributed to the dimensions of Mons Olympus.

A third factor has also played a role. The gravitational force acting on the mountain depends not only on the mass of the mountain, but also on the mass of the planet. With the mass of Mars about a tenth that of Earth, the weight of the volcano on the supporting rocks would have been considerably less than for a mountain of equal dimensions on Earth.

Vesta: mountains from impact

Beyond the orbit of Mars lies the asteroid belt. One of the largest of these asteroids, Vesta, provides evidence of mountain formation in the absence of either tectonics or magmatism. The lower hemisphere of Vesta was struck by a large impactor *c.* 1,500Ma ago (Schenk *et al.* 2012). With its mass being only 5×10^{-3}% of Earth's mass the result of this impact effectively rearranged the topography of half the asteroid in forming an impact crater >500km across, termed Rheasilvia (Fig. 6). Large impacts cause the rocks involved to behave like fluids, causing not only craters as the impacted rocks flow outwards, but also central peaks within the craters as the displaced rocks rebound. In this case the crater reached depths of 13km below the pre-impact surface and the central peak rose 22.5km from the crater floor. Although representing some of the most formidable topography in the Solar System the height of this peak rises a mere 9.5km above the pre-impact surface. A peak of Himalayan dimensions indeed, but given the low mass of Vesta, compared to Earth it is not one that would challenge the strength of the supporting rocks beneath it.

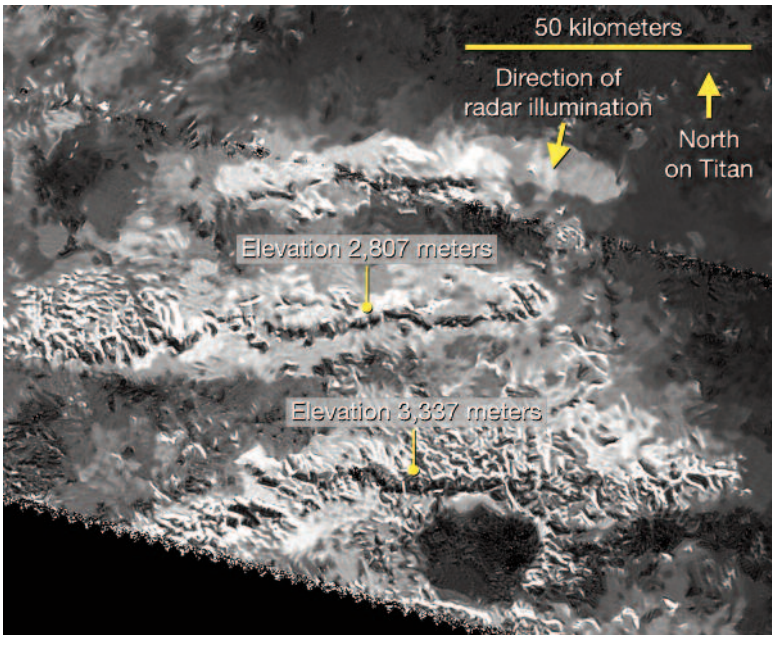
The mountains of Titan

Beyond the asteroid belt lie the gas planets of Jupiter, Saturn, Uranus and Neptune. Several of their moons are known to have mountain belts, and some of the best documented examples are on Titan, the largest moon of Saturn.

Titan's surface shows abundant evidence for tectonic activity. The rigid outer shell is a 200km thick layer of water ice, on the surface of which have formed independent mountains >1,400m high and cryovolcanic calderas up to 1,700m deep (Kelley *et al.* 2018). The highest mountain range is Mithrim Montes, which forms three parallel ridges reaching elevations of 3,337m (Fig. 7), located near Titan's equator. The driving force behind this tectonism is likely to be some combination of rotation from the spin of the moon, tidal deformation from the gravitational pull of Saturn, and contractural deformation as the moon loses internal heat. Perhaps the key question here is why are the mountains on Titan no higher than some modest mountain ranges on Earth, like the Pyrenees. Titan is much smaller than the Earth (0.02 of Earth's mass) and the density of the icy rigid layer forming the mountains is much less than for the rocks of Earth's mountains, so surely higher mountains on Titan might be possible?

The answer probably lies in the strength of the materials that makes up Titan's outer layers. Not only is the rigid outer shell made up of ice, rather than of silicate rock — which has characterised all the examples of mountains considered so far — but the sub-surface shell is an ocean of water-ammonia. It is highly likely that such a weak material as liquid water would be unable to sustain mountains of any great height regardless of the tectonic activity within the outer rigid shell. One way to test this hypothesis is to consider a second example of a planet or moon with a liquid sub-surface shell.

Figure 7 A radar image of Mithrim Montes on Titan (NASA/JPL-Caltech/ASI).



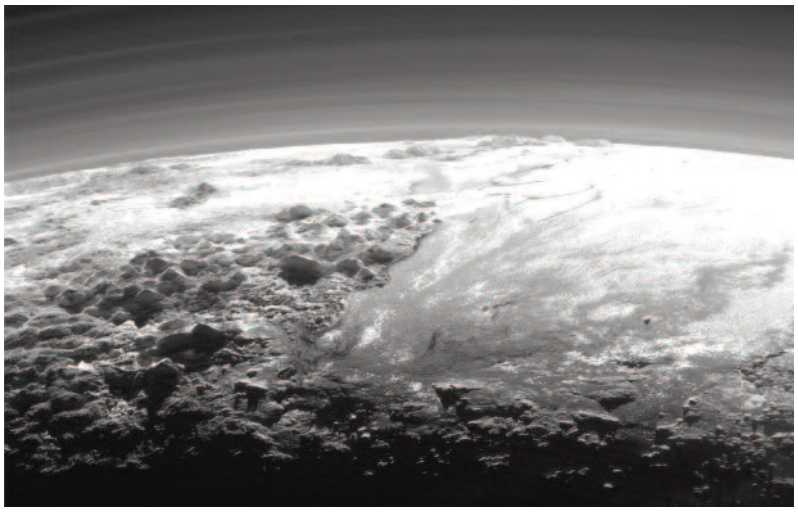


Figure 8 The highest mountains on Pluto: Tenzing Montes (6,200m) in the foreground and Hillary Montes in the distance (width of image c. 400km) (NASA/JHUAPL/SwRI).

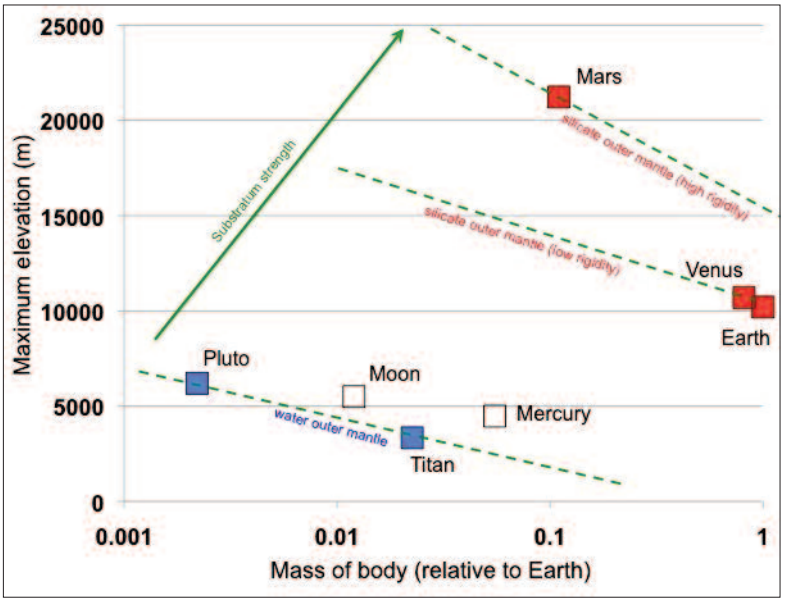
The mountains of Pluto

Pluto is a dwarf planet that lies in the Kuiper Belt outside the orbit of the outermost gas planet, Neptune. It shares with Titan a water-ice crust and a liquid water sub-surface shell. It also shares a variety of mountain ranges, the highest being Tenzing Montes, rising to 6,200m (Fig. 8) (Schenk *et al.* 2018). Little more is known about these distant hills except to note that they are almost double the altitude of Titan's highest peaks, even though both share a weak inner shell made predominantly of water. Perhaps this difference is related to their relative masses, Titan being ten times the mass of Pluto.

Conclusions

Looking beyond planet Earth can be revealing in terms of the physical processes that operate on a planetary scale (Fig. 9). The mountains of Venus tell us that mountains on a Himalayan scale can grow in the absence of plate tectonics, and that surface erosion is not required to limit their elevations from rising yet higher. From Mars we learn that sustained focussed magmatism, in the absence of plate tectonics, is one condition required to form massive volcanoes nearly three times the height of Mt Everest, but also rock strength must be sufficient to support the volcano. Mars provides rock strength at depth in lacking a plastic asthenosphere that provides the isostatic compensation depth on Earth. The outer Solar System provides evidence of sub-Himalayan scale mountain ranges on both Titan and Pluto, in both cases being supported by a weak sub-surface shell. In all examples, the heights that mountains can achieve are closely related to the strength of the materials that support them.

Figure 9 Diagram plotting the maximum elevation found on planetary bodies against planetary mass, with schematic isopleths for the relative strength of the outer mantle (dashed green lines). Red squares indicate planets with a silicate outer mantle; blue squares indicate bodies with water outer mantle. Note that this relationship can only apply where tectonism or magmatism is sufficient to achieve maximum possible altitudes. Where both tectonism and magmatism are relatively quiescent mountains of such high elevations will not be observed as seen on our moon and Mercury (open squares).



Acknowledgements

This presentation was the outcome of a question put to me by John Zarnecki (Professor Emeritus, The Open University) following my valedictory address in January 2019. He asked if I had ever considered the formation of mountains on planetary bodies beyond Earth. I had not, so this is a small step in rectifying that omission.

References

Anderson, F. S., and Smrekar, S. E. 2006 'Global mapping of crustal and lithospheric thickness on Venus'. *J Geophys Res: Planets* **111**(E8)

Cattin, R., Martelet, G., Henry, P., Avouac, J. P., Diament, M., and Shakya, T. R. 2001 'Gravity anomalies, crustal structure and thermo-mechanical support of the Himalaya of Central Nepal'. *Geophys J Internat* **147**, 381–92

Diao, F., Walter, T. R., Motagh, M., Prats-Iraola, P., Wang, R., and Samsonov, S. V. 2015 'The 2015 Gorkha earthquake investigated from radar satellites: slip and stress modeling along the MHT'. *Frontiers in Earth Science* **3**, 65

Egholm, D. L., Nielsen, S. B., Pedersen, V. K., and Lesemann, J. E. 2009 'Glacial effects limiting mountain height'. *Nature* **460**(7257), 884

Isherwood, R. J., Jozwiak, L. M., Jansen, J. C., and Andrews-Hanna, J. C. 2013 'The volcanic history of Olympus Mons from paleo-topography and flexural modeling'. *Earth Planet Sci Lett* **363**, 88–96

Kelley, L. 2018 'What has Cassini-Huygens discovered on Titan?'. https://owlcation.com/stem/Huygens-Mission-on-Titan [updated on November 15, 2018]

McKenzie, D., Barnett, D. N., and Yuan, D. N. 2002 'The relationship between Martian gravity and topography'. *Earth Planet Sci Lett* **195**, 1–16

Odell, N. E. 1967 'The highest fossils in the world'. *Geol Mag* **104**, 73–4

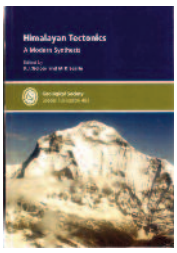
Powell, J. W. 1875 ''Physical features of the Colorado Valley'. *Pop Sci Month* **7**, 385–99

Schenk, P., O'Brien, D. P., Marchi, S., Gaskell, R., Preusker, F., Roatsch, T., Jaumann, R., Buczkowski, D., McCord, T., McSween, H. Y., and Williams, D. 2012 'The geologically recent giant impact basins at Vesta's south pole'. *Science* **336**(6082), 694–7

Schenk, P. M., Beyer, R. A., McKinnon, W. B., Moore, J. M., Spencer, J. R., White, O. L., Singer, K., Nimmo, F., Thomason, C., Lauer, T. R., and Robbins, S. 2018 'Basins, fractures and volcanoes: global cartography and topography of Pluto from New Horizons'. *Icarus* **314**, 400–33

Book review

Treloar, P. J., and Searle, M. J. (eds) 2019 *Himalayan Tectonics: A Modern Synthesis*. London: Geological Society Special Publication 483 (ISBN is 978-1-78620-405-9; vi + 669pp; hardback £160)



GSL Special Publication *Himalayan Tectonics* (Treloar and Searle 1993) contained 39 papers, and continues to be cited today. This hefty new volume contains 21 review papers, summarising the current state of knowledge and outlining some lines for future research.

Each of the papers is solidly grounded in detailed geological fieldwork, which goes back to the great Trigonometrical Survey begun in 1802 by William Lambton and continued by George Everest. The paper 'Karakoram Geotraverse' will have given many of us a taste of the challenges involved. Structural geology, geochemistry, mineralogy, isotope chemistry, geophysics, igneous and metamorphic petrology, and sedimentology are all utilised here.

Abstracts and a summary are available online at https://pubs.geoscienceworld.org/books/book/2208/Himalayan-Tectonics-A-Modern-Synthesis (accessed 20.01.2020). This webpage also gives access to open-access papers. These include Searle and Treloars's magisterial 'Introduction to Himalayan Tectonics', which summarises the current state of research, and suggests 20 unsolved problems and potentially fruitful directions for future research. O'Brien's paper on 'Eclogites and other high-pressure rocks in the Himalaya', and Bilham's 'Himalayan earthquakes' are also open access.

The remaining papers are grouped into five sections. Timings and stratigraphy (3 papers), NW Himalaya (5), Nepal Himalaya (5), Geophysics (2), Karakoram-Pamir-Tibet (4), Monsoon System (1). The last paper might one day form the nucleus of a new volume linking tectonics to climate change on a regional and world scale, perhaps linked to some palaeobotany.

The format of this book could be a bit larger, as some of the figures and plates seem small. Given the uniformity of lithologies and structure, apart from the syntaxes, a map, sections, basic information and a list of acronyms on an OU type bookmark would have been useful. The intended readership will probably not need this.

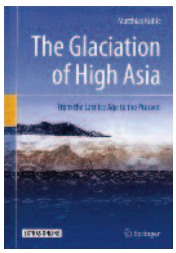
There is clearly much work to be done in the Himalayas in the next 25 years, but this is a landmark synthesis of the current state of knowledge, and lays the foundations for much future work.

By any reckoning this is an expensive volume, and probably beyond the budget of many of us. If you are serious about research and this is your field area, then you will need your own copy. Otherwise, this is one to borrow from a library. The more general reader may prefer M. J. Searle's book *Colliding Continents: A Geological Exploration of the Himalaya, Karakoram, and Tibet*.

— Peter Blackett BSc (Hons) (Open)

Book review

Kuhle, Mathaias 2018 T*he Glaciation of High Asia from the Last Ice Age to the Present*. Cham: Springer International Publishing AG (ISBN 978-3-319-77564-7; 300pp; hardback £89.50)



As its title suggests, this is a comprehensive review of High Asian glaciation, by an author who has been on many occasions to the areas he describes in detail.

Some names are familiar from Edmund Hillary's description of the ascent of Everest — e.g. Kumbu, Rongbok glaciers and Tien Shan and Karakoram mountains.

The plentiful, clear and annotated photographs are by the author and from Google Earth Pro Microsoft Bing satellite.

Kuhle has sampled the deposits of glacial moraine and glacial till from many sites. He includes colour photos of many rocks, as well as the colour plates of contemporary mountains and of the Indus Valley with ground moraines and U-shaped valleys.

At least 15 stages in the glaciation can be shown, with radiocarbon dating correlating the ages. Kuhle has estimated the preglacial heights of the mountains and indicated these on the photos. In exposed granite areas comparisons are made with Dartmoor and Finland.

Sample analyses of sediments show clays, limestone and quartz. Some boulders in the till areas are more than 4m in size at an altitude of 5,340m above sea level. Ground moraine has been noted at 6,000m above sea level.

The book is divided into six sections and includes a preface and a postscript by the author's wife, explaining that final editing was not done by her husband, as he had died before publication.

The sections are:

1 Method
2 Research areas (of which there are 52 with cross-references and summaries)
3 Chronology
4 Overall picture
5 Paleoclimatic significance
6 Nourishment areas.

Although too heavy for bedtime reading, this book is nicely produced with glossy paper and clear printing.

— Rosemary Darby, BA (Open), BSc (Hons) (Open), Certs Ed. UK, NZ

How rocks flow, and why we care

Giulia Degli Alessandrini

The Open University

Dr Degli Alessandrini was unable to write up her lecture for an OUGS Proceedings *article. Below is an abstract of her lecture, slightly edited, in [brackets] — Editor.*

Rocks, as we know them, are solid, cohesive aggregates of grains of one or more minerals. It is therefore hard to imagine that rocks can behave like fluids, with properties similar to toothpaste.

Yet, in the deep crust — below the crust's brittle–ductile transition [zone] — rocks [are] subject to stress, flow like viscous fluids, and deform. While the conditions necessary for rocks to flow can be reproduced in laboratory experiments, nature provides direct evidence of this flow within shear zones: localised structures made of highly deformed rocks, surrounded by undeformed rocks.

This talk [explored] how geologists study naturally deformed rocks from shear zones to understand how rocks flow in the deeper [parts] of the Earth's crust. [The speaker] explain[ed] some background knowledge on the topic and highlight[ed] some outstanding controversies. [She presented] the analytical techniques involved — from sample collection in the field, to the use of electron microscopy in the lab (e.g. electron backscatter diffraction for determining crystallographic orientation of grains in space).

[She gave her reasons] why this topic of research is relevant to our broader understanding of the geodynamics of our planet.

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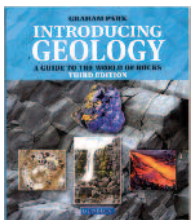
Book review

Park, Graham 2019 *Introducing Geology: a Guide to the World of Rocks* (3rd edn). Edinburgh: Dunedin (ISBN 978-1-780460-75-8; 134pp; paperback £9.99)



This little book, packed full of information, is one of a series of 'Introducing …' volumes published by Dunedin. It is a useful reference book for those starting a study of geology or returning to study. I have been using the first edition (and subsequent Dunedin guides) with my two groups of U3A adult learners for the past couple of years, as a substitute for a school textbook and as a basis for the monthly talks I give. My 'senior' students have found it much more appropriate to adult learners than a school textbook: they commented that the glossary was particularly useful and the text easy to understand. The language is accessible and the text richly supplemented by many colour photographs and diagrams.

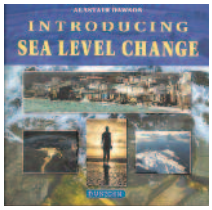
The 11 chapters start with a brief study of crystals and minerals, go on to looking at volcanoes, erosion and sediments, followed by earth movements and rock deformation. Fossils and geological time are also considered, and the final chapters look at Earth history and continental movements and finish by exploring the relationship between industry and man. Thus, the full gamut of geological study is presented in a nutshell!

The small format, wealth of information and modest price make this a very useful addition to my bookshelf.

— Mary Howie, BA (Hons) Open

Book review

Dawson, Alastair 2019 *Introducing Sea Level Change*. Edinburgh: Dunedin (ISBN 978-1-78046-087-1, 91pp; paperback £14.99; also as ePub 978-1-78046-600-2 and Kindle 978-1-78046-601-9)



For a book with 'Introducing' in the title I found this quite a technical read. It felt a little rushed in places, as the text did not quite seem to connect fully with all the figures or the figures would have benefitted from more labelling.

The author first addresses what 'sea level' means. From the start the reader will realise that the topic is much more complicated than it first appears, and by the end I fully agree with his summary that it is "exceptionally complex".

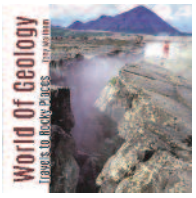
The early chapters look at the evidence, chronologies and interpretation of past sea level changes before leading into physical aspects of surface-loading and processes of sea level change. Later chapters cover sea level change relating to glaciation and ice sheets.

The final chapters bring all this together to explain why the idea of a global sea level curve has become unworkable, the implications for present and future sea level and a summary of understanding sea level change.

— Helen Coombs, BSc (Hons) Geosciences (Open)

Book review

Waltham, Tony 2019 *World of Geology: Travels to Rocky Places*. Caithness: Whittles Publishing (ISBN 978-1-84995-437; 219pp; paperback, £18.99)



Many of the locations on a 'geologist's bucket list' have been captured by Tony Waltham in this delightful and interesting book. I first encountered some of the wonderful pictures — really 'geo-art' — on the back cover of *Geology Today*, where they had become a permanent feature, accompanied by an informative explanation. I had also visited some of these far-flung places with Tony as a great, and supremely organised leader and guide, so favourite places have been revisited!

The enthusiasm with which readers received the pictures on *Geology Today* covers spawned the idea of gathering them, together with others from his archive, to form this book: 110 square-format photographs, with excellent geological and engineering discussion on the opposite pages, take a tour around all the continents — except Antarctica!

The book starts with a Table of Contents, a short preface to explain how the book came about and a good introduction, which explains relationships between geology, landscape and how processes shown in the pictures relate to plate tectonics; this is enhanced by a cross-section indicating all the geological processes relating to converging and diverging plate boundaries — which should be familiar to all OU students of geology! There is also a world location map to show where all the pictures were taken.

Tony has a mining and engineering geological background — that and his fanatical interest in cave systems and their exploration have been the trigger for many of the pictures, which show both recent and ancient geological phenomena. Reading this book affirms geology in action.

Some of the pictures I particularly relish: flash floods in Nizwa (76) (having stood on that car park!), The Gibeon iron meteorites (66), the fire fountain on Mount Etna (62) — and for showing Tony's sheer photographic skills, Rock blasting at Cheddar Gorge (53). Classic English geological locations also feature, including Chevron folding at Millock Haven (54) and Malham Cove in the Lower Carboniferous of the Yorkshire Dales (46). Two of the most spectacular (one natural and one man-made) are the cover illustration, Plate divergence at Myvatn (38) and Pipeline over permafrost (34) — the Trans-Alaska oil pipeline.

Although there is a numerical Table of Contents, an index of places and processes would have been a welcome addition. The titles of some of the pictures are rather long, the arrangement is location-based rather than alphabetical, so finding a specific photo can be difficult; hence the use of the numbers to enable those who wish to find the superb pictures that I found so interesting.

I like the square format, but the photos do not appear as 'crisp' as they do on the back of *Geology Today*, which is a pity given both the geological and artistic worth of this sumptuous collection — an ideal fireside book for winter planning of your next geological expedition and a bargain at £18.99.

— Diana M. Smith, BA (Open), BSc (Hons) Geology (Birkbeck, London), FGS

Ancient rain: uncovering the past response of the Indian Monsoon to climatic changes

Katrina Nilsson-Kerr

The Open University

Introduction

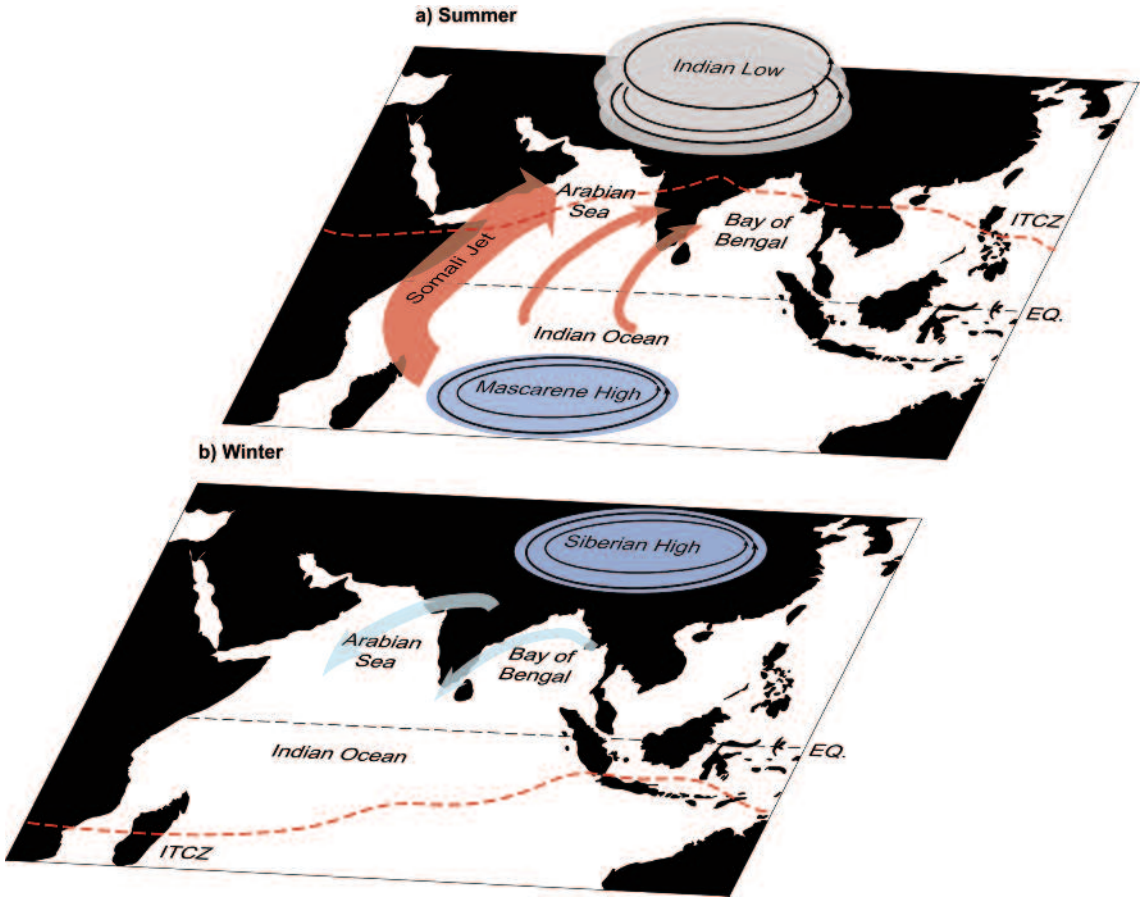
Every year in June, intense winds and rainfall reach India and the surrounding region where they persist until September. This seasonal phenomenon, the Indian Summer Monsoon (ISM), represents one of the most dynamic interactions of ocean–atmosphere–terrestrial processes operating on Earth today. This unique system plays a prominent role in dictating the socio-economies of the 1.7 billion people inhabiting the ISM-affected region; extreme rainfall can lead to flooding, infrastructure and crop damage, while periods of reduced monsoon strength can result in drought and food shortages. This delicate relationship between society and nature is becoming increasingly strained owing to a rising occurrence of anomalous ISM behaviour in response to human-induced climate change. Looking forward, it is critical that we have a comprehensive understanding of how the monsoon may behave associated with a rise in global temperature and atmospheric greenhouse gas concentrations. Earth's geological past presents a natural case study for reconstructing how the monsoon once responded to changes in climate, thereby providing clues useful for better predicting its future behaviour.

Indian Monsoon dynamics

Originating from the early theory of Halley (1686), the Indian Monsoon can be viewed simply as a reversal of winds in response to a change in the temperature contrast between the land versus the adjacent Indian Ocean. During the spring and summer months the overhead sun heats up the land, promoting the prevailing winds to change direction from north-easterly to south-westerly (Fig. 1), heralding the ISM onset. Additionally, the ISM can be viewed as the subtropical manifestation of the Inter-Tropical Convergence Zone (ITCZ), a band of concentrated rainfall that moves preferentially towards the warmer hemisphere. This rainfall north of the Equator is associated with Hadley Cell atmospheric circulation, and its subsequent meridional movement and strength (and therefore, ISM strength) is dependent upon energy fluxes. Thus, combined mechanisms that act to weaken the land-ocean temperature contrast, as well as reduced energy fluxes from the extra-tropics, promotes weaker monsoonal activity.

The combination of intense rainfall and wind strength associated with the ISM exerts a pronounced influence on the upper water column structure of both the Arabian Sea and the Bay of Bengal,

Figure 1 Schematic diagram of the main components of the Indian Monsoon: (a) heating of the Tibetan Plateau during boreal spring promotes a zone of low pressure (Indian Low) while an anticyclone (Mascarene High) forms over the cooler Indian Ocean; (b) the Indian Winter Monsoon is associated with north-easterly winds (blue arrows) bringing cold, dry air from the Asian landmass accompanied by a southward migration of the ITCZ.



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located west and east of the Indian subcontinent, respectively (*see* Fig. 1). The Bay of Bengal is characterised by a unique freshwater signal; ISM rainfall feeds the 12 major rivers, including the Ganges-Brahmaputra river systems, resulting in a net freshwater delivery of $942 \times 109 m^3$ (Varkey 1996). The surface waters in the Bay of Bengal are highly stratified with a lens of fresh, low-saline water in the upper 50m of the water column, thereby suppressing any influence of wind mixing by the strong south-westerly winds. In contrast, the Arabian Sea lacks any significant freshwater input and the water column is subsequently well mixed owing to the influence of the summer monsoon winds.

Past monsoon: legacy studies

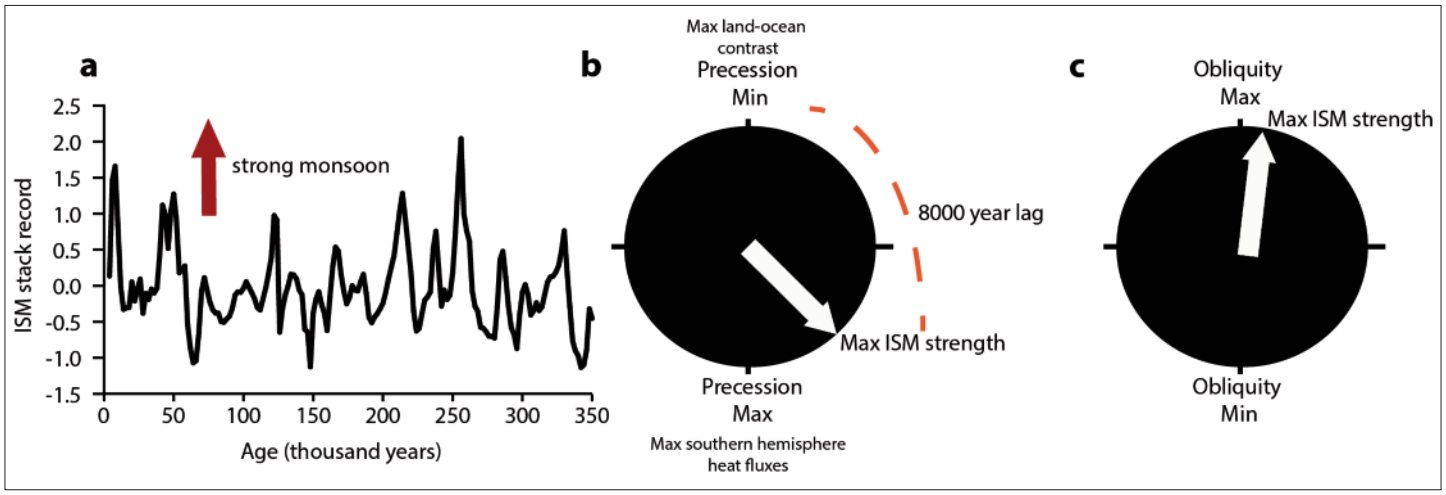
The 1960s is famously attributed to being the decade of the space race. However, not only were scientists pushing the boundaries of technology and innovation to reach the outer limits of Earth, but also to reach deep within its inner depths. The Deep-Sea Drilling Project (DSDP, 1968–1985) — also subsequently known as the Ocean Drilling Program (ODP, 1985–2004), Integrated Ocean Drilling Program (IODP, 2004–2013), and the International Ocean Discovery Program (also IODP, 2013–present) — emerged during this era of scientific progress permitting the retrieval of long, continuous records of climate history locked up in ocean sediments. It was in 1987, during ODP Leg 117, that the north-east Arabian Sea was targeted as a location suited for retrieving ocean sediment cores that would shed light on the "origin, evolution and variability of the Indian Monsoon". The third aim — reconstructing the past variability of the Indian Monsoon — is most relevant, considering future climate change.

The expression of the ISM within the Arabian Sea is dominated by wind-induced upwelling and subsequent pumping of nutrients into the surface ocean, sustaining surges in biological activity. This boom in primary productivity is subsequently responsible for the widespread development of oxygen minimum zones as increasing amounts of oxygen becomes consumed. Clemens *et al*. (1991) and Clemens and Prell (2003) exploited a range of biological, geochemical and lithological climate proxies with an affinity for capturing past changes in productivity and monsoonal wind mixing. Wind-induced upwelling can influence the plankton assemblage within the water column; the sub-polar surface-dwelling foraminifera species *Globigerinoides bulloides* has been shown to be present within tropical regions during periods of increased upwelling of nutrient-rich cold waters. Thus, tracking changes in the percent abundance of these fossil carbonate shells can be used as a proxy for changes in ISM-induced upwelling within the Arabian Sea. Additionally, oxygen minimum zone intensity can be reconstructed through the nitrogen isotopic composition ($d^{15}N$) of bulk sediments. Finally, changes in lithogenic grain size of ocean sediments may have changed as a function of wind strength variations.

These proxies were all combined by Clemens and Prell (2003) to produce a record of the ISM across the glacial-interglacial cycles of the Late Pleistocene *c.* 350ka to the present) (Fig. 2a). In order to assess the response of a component of the internal climate system (in this case, the monsoon) it is necessary to compare with both the main Earth system input (insolation, i.e. the received energy from the Sun) with other internal climate parameters (e.g. ice volume). The Arabian Sea ISM record revealed the occurrence of strong monsoon winds 8,000 years after the occurrence of peak northern hemisphere solar insolation (NHSI) (Fig. 2b). Periodical changes in Earth's axis (precession) every 23,000 years controls the hemispheric distribution of incoming solar radiation. During precession minima, northern hemisphere summers occur at perihelion (Earth's closest point to the Sun), and thus the northern hemisphere receives more incoming solar radiation.

It was initially interpreted that this orbital configuration is essential for influencing strong monsoons to occur as a result of an enhanced land–sea thermal contrast (Kutzbach 1981). However, the lag of 8,000 years with respect to peak NHSI that was found in the Arabian Sea ISM record highlighted modulation of monsoon strength by additional internal mechanisms. Clemens and Prell (2003) instead proposed that ISM strength is indirectly influenced by external orbital forcing via changes in ice volume and greenhouse gas concentrations — thereby, influencing changes in the land-sea thermal gradient — but that the ISM is additionally forced by southern hemisphere climate-forcing owing to the observed phase relationship found in the obliquity band (Fig. 2c). Southern hemisphere climate-forcing of the monsoon is attributed to latent heat fluxes being transported across

Figure 2 (a) Arabian Sea Indian Summer Monsoon (ISM) stacked proxy record; (b) precession-band phase wheel highlighting the timing of strong monsoons occurring 8,000 years after June 21 Perihelion and its associated maximum sensible heat influence (land-ocean contrast); and (c) obliquity-band phase wheel highlighting timing of strong monsoons occur in-phase with obliquity maxima. During obliquity maxima, latent heat fluxes from the southern hemisphere are maximised owing to greater hemispheric seasonality (adapted from Clemens and Prell 2003).



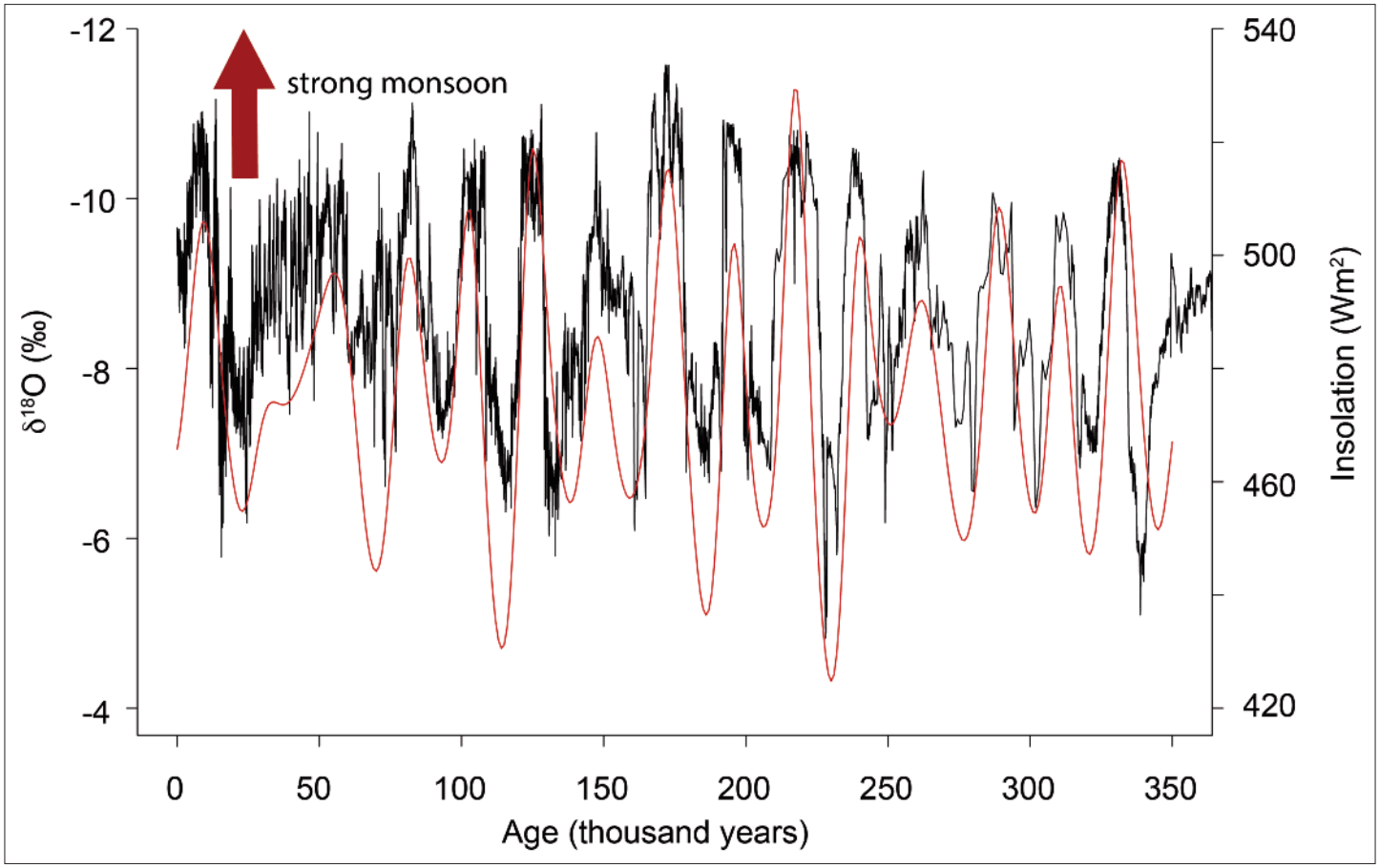


Figure 3 Southern Chinese speleothem $\delta^{18}O$ (black) plotted against insolation at June 65°N (red line = maximum northern hemisphere solar insolation) (Laskar et al. *2004).*

the Equator from the southern Indian Ocean when Earth's tilt is greatest (obliquity maximum promoting enhanced seasonality), providing moisture and heat necessary for monsoonal circulation (Clemens and Prell 2003).

Past monsoon: the plot thickens

The portrayal of the monsoon arising from ODP Leg 117 presented a view of the monsoon from a single marine setting, the Arabian Sea, based on proxies capturing inferred wind strength. Yet the monsoon encompasses a large region, both on land and in the marine realm, with both a rainfall and wind signature. A subsequent proliferation of palaeoclimate studies occurred across the early 21st century in order to provide further constraints on the sensitivity and mechanisms determining monsoonal behaviour. Most notably, an alternative picture of the orbital-scale monsoon emerged following the recovery of cave (speleothem) records from southern China. Speleothems have a unique advantage compared to marine records, as they can be absolutely dated through U-series radiometric dating and offer greater temporal resolution. Past changes in rainfall amount, and thereby monsoonal strength, have been interpreted to be reflected in the oxygen isotopic composition ($\delta^{18}O$) of speleothem calcite (Cheng *et al.* 2016, 2009; Wang *et al.* 2008).

The speleothem $\delta^{18}O$ records cite the strength of NHSI as being the main driving force of the Asian Monsoon as a whole (the term used to encompass the two monsoonal subsystems affecting the Asian landmass; the ISM and the East Asian Summer Monsoon) owing to the close correlation between speleothem $\delta^{18}O$ and NHSI (Fig. 3). This support for the monsoon being solely regulated by northern hemisphere climate processes through an influence on the land–sea thermal gradient is in strong contrast to the interpretation of monsoon sensitivity proposed in the foundational Arabian Sea study (Clemens *et al.* 1991; Clemens and Prell 2003). Subsequent studies provided support for both the interpretation of monsoon sensitivity from the Arabian Sea (Bolton *et al.* 2013; Caley *et al.* 2011; Gebregiorgis *et al.* 2018) and that from the speleothem $\delta^{18}O$ record (Cai *et al.* 2015; Kathayat *et al.* 2016).

Further, the authenticity of the monsoon signal recorded in the climate proxies applied in both the Arabian Sea and the speleothem $\delta^{18}O$ was questioned. Studies suggested that the inferred ISM signal within the Arabian Sea may be tainted by the effects of the winter monsoon winds (Le Mézo *et al.* 2017) or by nutrient delivery via oceanic circulation (Ziegler *et al.* 2010). Furthermore, the interpretation of speleothem δ18O as representing monsoon rainfall amount may be too simple, neglecting potentially complex moisture transport processes (Caley *et al.* 2014; Pausata *et al.* 2011).

Recent work: the Bay of Bengal

A new wave of monsoon-related drilling expeditions was undertaken by the IODP starting in 2013 in an attempt to reconcile discrepancies in past monsoon understanding. It was during IODP Expedition 353 that locations within the Bay of Bengal were drilled in order to provide sediments that would capture a primary monsoon rainfall signature, thereby avoiding

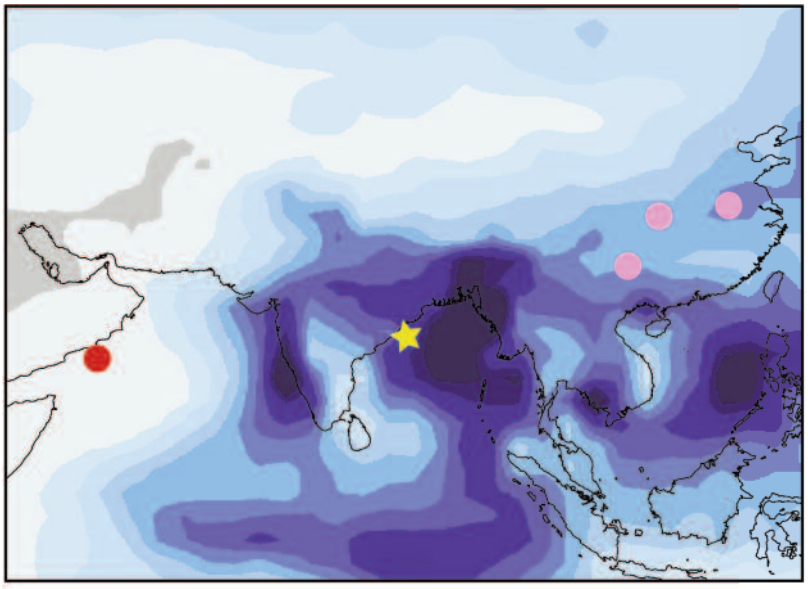


Figure 4 Map of studies discussed in this article: red circle = Arabian Sea study (Clemens and Prell (2003); pink circles = Chinese speleothem record (Cheng et al. *2009, 2016); yellow star = northern Bay of Bengal study (Nilsson-Kerr* et al. *2019); base map represents precipitation (mm/month) in July (http://iridl.ldeo.columbia.edu); darker blue represents more intense rainfall highlighting the Bay of Bengal to be the core rainfall region.*

potential biases and questions about the fidelity of the recorded monsoon signal.

The application of paired $\delta^{18}O$ and sea-surface temperature estimates derived from the ratio of magnesium versus calcium in the shell of surface-dwelling foraminifera has been widely applied in paleoceanographic studies, as the $\delta^{18}O$ of seawater ($\delta^{18}O_{sw}$) can be derived from such temperature estimates, which can act as a proxy for surface ocean freshening (salinity). The application of this technique is well suited to the Bay of Bengal, which undergoes a prominent surface freshening explicitly during the summer months from its receipt of monsoon rainfall and river runoff. Additionally, accompanying freshwater input via riverine runoff is an influx of terrestrial material associated with intense chemical weathering as a result of the monsoon rainfall. The Ganges-Brahmaputra alone contributes 1.06×10^9 tonnes of sediment annually (Milliman and Syvitski 1992).

Thus, proxies that capture changes in the strength of terrestrial fluxes can further inform past ISM behaviour.

Ocean sediments can be analysed using X-ray fluorescence techniques in order to gain information on bulk elemental concentrations; certain elements (e.g. Al, K and Rb) are preferentially found in aluminosilicates and fine clay fractions representing material derived from the continent. Nilsson-Kerr *et al.* (2019) presented a record of the ISM consisting of surface dwelling foraminiferal $\delta^{18}O_{sw}$ and bulk element concentrations inferred to represent terrigenous input across the penultimate deglaciation (*c.* 139–127ka ago) from the northern Bay of Bengal (Fig. 4).

It was shown that during climate warming *c.* 130Ma ago, the Indian Summer Monsoon strengthened in response to southern hemisphere warming while the northern hemisphere remained largely in a glacial state (Fig. 5). Nilsson-Kerr *et al.* (2019) interpreted the monsoon to have undergone an initial deglacial strengthening caused by heat and moisture fluxes being transported across the Equator from the warm southern hemisphere. This strengthening of the ISM is inferred to have been influential in subsequently promoting northern hemisphere deglaciation as a result of heat and moisture transport from across the Equator.

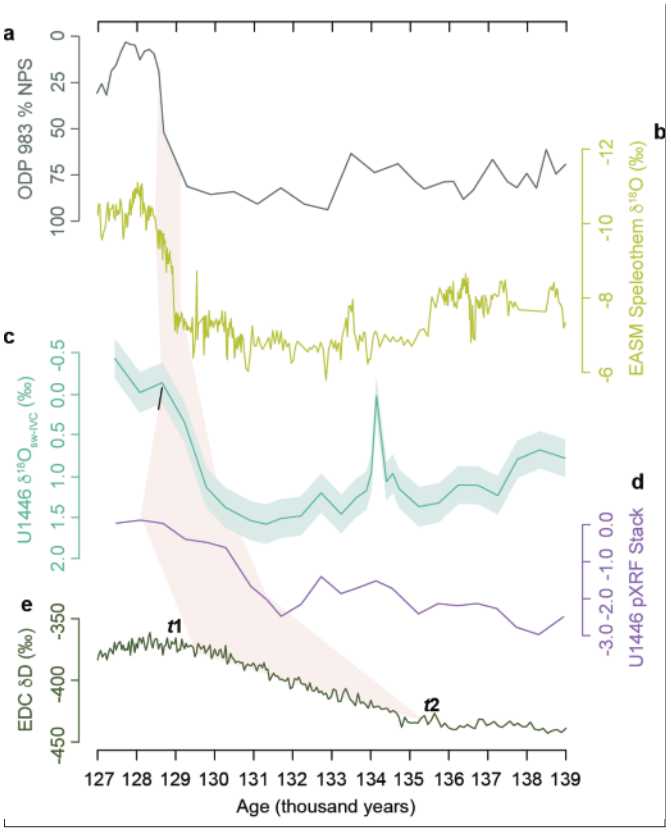
Thus, this record of the ISM across a glacial–interglacial transition highlights the ISM as being sensitive to climate changes in both the northern and southern hemisphere, thereby providing support for the initial interpretation of monsoon sensitivity presented by Clemens and Prell (2003).

Outlook

Understanding of the past Indian Monsoon has been rapidly evolving over the past several decades using analytical advancements associated with ocean drilling, proxy development and model simulations. A complete understanding of how the monsoon has behaved in response to changes in climate and how the monsoon is predicted to behave in response to future climate change remains elusive owing to potential complications with climate proxy signals. Studies of the ISM to date highlight that monsoon behaviour is incredibly sensitive to climate changes occurring in both the southern and northern hemisphere (Bolton *et al.* 2013; Clemens and Prell, 2003; Nilsson-Kerr *et al.* 2019); and that its behaviour even plays a role in communicating climate signals between the hemispheres (Nilsson-Kerr *et al.* 2019). Thus, there remains a need for increased generation of data records across the monsoon-affected region, as well as the integration of data records with climate models.

Understanding of the past monsoon is incredibly dynamic and remains, now more than ever, essential in light of human-induced climate change.

(caption opposite)



References

Barker, S., Chen, J., Gong, X., Jonkers, L., Knorr, G., and Thornalley, D. 2015 'Icebergs not the trigger for North Atlantic cold events'. *Nature* **520**, 333–6

Bolton, C. T., Chang, L., Clemens, S. C., Kodama, K., Ikehara, M., Medina-Elizalde, M., Paterson, G. A., Roberts, A. P., Rohling, E. J., Yamamoto, Y., and Zhao, X. 2013 'A 500,000 year record of Indian summer monsoon dynamics recorded by eastern equatorial Indian Ocean upper water-column structure'. *Quat Sci Rev* **77**, 167–80

Cai, Y., Fung, I. Y., Edwards, R. L., An, Z., Cheng, H., Lee, J.-E., Tan, L., Shen, C.-C., Wang, X., Day, J. A, Zhou, W., Kelly, M. J., and Chiang, J. C. H. 2015 'Variability of stalagmite-inferred Indian monsoon precipitation over the past 252,000 y'. *Proc Nat Acad Sci USA* **112**, 2954–9

Caley, T., Malaizé, B., Zaragosi, S., Rossignol, L., Bourget, J., Eynaud, F., Martinez, P., Giraudeau, J., Charlier, K., and Ellouz-Zimmermann, N. 2011 'New Arabian Sea records help decipher orbital timing of Indo-Asian monsoon'. *Earth Planet Sci Lett* **308**, 433–44

Caley, T., Roche, D. M., and Renssen, H. 2014 'Orbital Asian summer monsoon dynamics revealed using an isotope-enabled global climate model'. *Nat Commun* **5**, 5371

Cheng, H., Edwards, R. L., Broecker, W. S., Denton, G. H., Kong, X., Wang, Y., Zhang, R., and Wang, X. 2009 'Ice age terminations'. *Science* **326**, 248–52

Cheng, H., Edwards, R. L., Sinha, A., Spötl, C., Yi, L., Chen, S., Kelly, M., Kathayat, G., Wang, X., Li, X., Kong, X., Wang, Y., Ning, Y., and Zhang, H. 2016 'The Asian monsoon over the past 640,000 years and ice age terminations'. *Nature* **534**, 640–6

Clemens, S. C., Prell, W., Murray, D., Shimmield, G., and Weedon, G. 1991 'Forcing mechanisms of the Indian Ocean monsoon'. *Nature* **353**, 720–5

Clemens, S. C., and Prell, W. L. 2003 'A 350,000 year summer-monsoon multi-proxy stack from the Owen Ridge, Northern Arabian Sea'. *Mar Geol* **201**, 35–51

Gebregiorgis, D., Hathorne, E. C., Giosan, L., Clemens, S., Nürnberg, D., and Frank, M. 2018 'Southern Hemisphere forcing of South Asian monsoon precipitation over the past ~1 million years'. *Nat Commun* **9**, 4702

Halley, E. 1686 'An Historical Account of the Trade Winds, and Monsoons, Observable in the Seas between and Near the Tropicks, with an Attempt to Assign the Phisical Cause of the Said Winds, By E. Halley'. *Philos Trans Roy Soc Lon* **16**, 153–68

Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J.C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Werner, M., and Wolff, E. W. 2007 'Orbital and millennial Antarctic climate variability over the past 800,000 years'. *Science* **317**, 793–6

Kathayat, G., Cheng, H., Sinha, A., Spötl, C., Edwards, R. L., Zhang, H., Li, X., Yi, L., Ning, Y., Cai, Y., Lui, W. L., and Breitenbach, S. F. M. 2016 'Indian monsoon variability on millennial-orbital timescales'. *Sci Rep* **6**, 24374

Kutzbach, J. E. 1981 'Monsoon climate of the early Holocene: climate experiment with the Earth's orbital parameters for 9,000 years ago'. *Science* **214**, 59–61

Le Mézo, P., Beaufort, L., Bopp, L., Braconnot, P., and Kageyama, M. 2017 'From monsoon to marine productivity in the Arabian Sea: insights from glacial and interglacial climates'. *Clim Past* **13**, 759–78

Milliman, J. D., and Syvitski, J. P. M. 1992 'Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers'. *J Geol* **100**, 525–44

Mudelsee, M. 2000 'Ramp function regression: a tool for quantifying climate transitions'. *Comput Geosci* **26**, 293–307

Nilsson-Kerr, K., Anand, P., Sexton, P. F., Leng, M. J., Misra, S., Clemens, S. C., and Hammond, S. J. 2019 'Role of Asian summer monsoon subsystems in the inter-hemispheric progression of deglaciation'. *Nat Geosci* **12**, 290

Pausata, F. S. R., Battisti, D. S., Nisancioglu, K. H., and Bitz, C. M. 2011 'Chinese stalagmite $\delta^{18}O$ controlled by changes in the Indian monsoon during a simulated Heinrich event'. *Nat Geosci* **4**, 474–80

Varkey, J. M. 1996 'Physical oceanography of the Bay of Bengal and Andaman Sea'. *Ocean Mar Biol Ann Rev* **34**, 1–70

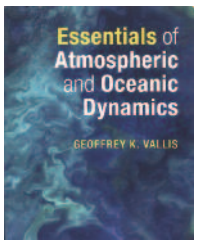
Wang, Y., Cheng, H., Edwards, R. L., Kong, X., Shao, X., Chen, S., Wu, J., Jiang, X., Wang, X., and An, Z. 2008 'Millennial- and orbital-scale changes in the East Asian monsoon over the past 224,000 years'. *Nature* **451**, 1090–3

Ziegler, M., Lourens, L. J., Tuenter, E., Hilgen, F., Reichart, G. J., and Weber, N. 2010 'Precession phasing offset between Indian summer monsoon and Arabian Sea productivity linked to changes in Atlantic overturning circulation'. *Paleoceanogr* **25**, PA3212

Figure 5 The onset and timing across the penultimate deglaciation (Termination II): (a) percent abundance of polar species foraminifera Neogloboquadrina pachyderma *in the North Atlantic (ODP Site 983) — decreased abundance of this foraminifera species is applied as a proxy for warming (Barker* et al. *2015); (b) Chinese speleothem $\delta^{18}O$ (Cheng* et al. *2016); (c) Northern Bay of Bengal (IODP Site U1446) surface dwelling foraminifera $\delta^{18}O_{sw}$ as a proxy for surface freshening — more negative values indicate surface freshening and thus a stronger monsoon (Nilsson-Kerr* et al. *2019); (d) Northern Bay of Bengal (IODP Site U1446) bulk sediment elemental concentrations (Rb, Al, K and Ti) representing terrigenous input derived using X-ray fluorescence techniques; and (e) Epica Dome C Ice-Core (Antarctica) δD as a proxy for temperature — more negative δD represents warmer conditions (Jouzel* et al. *2007). Pink shaded area denotes t2 (deglaciation onset) and t1 (attainment of warm interglacial conditions) as modelled using statistical RAMPFIT methods (Mudelsee 2000).*

Book review

Vallis, Geoffrey K. 2019 *Essentials of Atmospheric and Oceanic Dynamics*. Cambridge UP (ISBN 978-1-107-69279-4; 356pp; paperback £39.99)



It has never been a better time to work in atmospheric and ocean dynamics. Its practitioners are the profits of our future doom (or routes to salvation) and also deliver daily weather forecasts. Advances in computer power now give us simulations of unprecedented accuracy and detail. Fluid dynamics may be the unsexy end of physics, but in my own astrophysics PhD, I found it both unexpectedly useful and also the gateway to a computational physics industrial career. This book provides a good introduction to widely applicable skills and knowledge, while also demonstrating specific and timely relevance.

The review of the relevant basic physics is excellent and presented from parallel and equivalent viewpoints, that of an observer standing still while fluids move past and that of someone carried with the fluid. Although these are mathematically equivalent, the one can be more useful for practical computation, while the other often connects more closely with physical intuitions. The combination works well. Although the exposition is essentially mathematical, the derivations are well explained and we never loose sight of the underlying physics.

I liked the discussion of modelling approximations. Fast computers now permit high-resolution numerical simulation, but approximations are still involved in the many trade-offs between scope, physical fidelity, resolution and getting results in a reasonable time. Furthermore, dealing with simplified models can often give better insight into the relative importance of the underlying processes driving atmospheric and oceanic phenomena. (One of the reasons we have for trusting complex simulations is that we think that those who configure and run the codes have enough physical insight to understand the limitations of their models.)

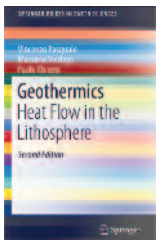
Part I of the book deals with all the standard topics one would expect in an introductory text, leaving you at a point where you could start to read more specialised literature. Part II, indeed, covers a few topics in more depth, and I have to admit to quickly seeking the chapter on Planetary Atmospheres, just as soon as I had covered the essential supporting material in Part I, where I found a good overview that dealt with the scaling parameters that make atmospheres similar or different. Other topics include, for example, the stratosphere, ocean gyres, and El Niño.

The book is targeted at advanced undergraduates, graduate students, beginning researchers or interested non-specialists wanting an accessible introduction to the field. (I regard myself as one of the last listed.) The level of treatment seems to be well judged for this context, though you do need a modest facility with vector calculus and thermodynamics — typically acquired after a couple of years of university physics or applied maths. (A relatively narrow range of knowledge is used intensively: after a few chapters you will become fluent even if you are not at the start!) There is little to be gained by just reading the words and skipping the equations (unlike some OU physics texts — even at Level 3 — where you can still gain useful insights by leaving the harder derivations to a second reading).

— Michael McEllin MA, PhD, BSc (Open), MSc (Open), FInstP, FRAS

Book review

Pasquale, Vincenzo, Verdoya, Massimo, and Chiozzi, Paolo 2017 *Geothermics: Heat Flow in the Lithosphere* (2nd edn). Cham: Springer (Briefs in Earth Sciences) (ISBN 978-3-319-52084-1; 144pp; eBook)



The great Scottish geologist James Hutton (1726–1797) conceived of the Earth as a ‘heat engine’, in which heat from an internal source is transferred outwards to drive the various processes of the rock cycle. The origin of the Earth’s internal heat was unknown in his day and the science of heat transfer was in its infancy. Today we have a greater insight into these thermal processes within the Earth. This short book aims to provide a concise review of some of our current understanding in this area.

The book comprises six chapters. Following an introductory chapter, the next three chapters concentrate on conductive heat transfer within both continental and oceanic lithosphere. The second chapter in particular discusses in some detail the nature of thermal conduction and provides a detailed description of both steady-state and transient methods for its measurement in minerals, rocks and wet sediments. Chapter five reviews convective heat transfer within groundwater and hydrothermal systems, a topic that is of particular relevance to the exploitation of geothermal energy. The final chapter demonstrates that long timescale variations in ground surface temperature propagate downwards by conduction to perturb the local geotherm. Such perturbations can be measured in deep boreholes and can, in some circumstances, be inverted to infer surface paleotemperatures that contribute towards reconstruction of past climates.

This book is one of a series of monographs published in the series ‘Springer Briefs in Earth Sciences’. It is thus particularly useful for anyone with a specific interest in geothermics, who does not want to delve into a more comprehensive geophysics book, such as Turcotte and Schubert’s *Geodynamics*. The book is suitable for students of Earth Sciences, at the senior undergraduate level or beyond, who are comfortable with a mathematical development of the topic. James Hutton would have been fascinated to read this concise review of progress made in understanding his ‘heat engine’ over the past two centuries.

— Duncan Woodcock, MA (Cantab), BSc (Hons) (Open), PhD
Continuing ES student

Phytoliths: a modern ecological perspective

Julia Cooke

The Open University

Introduction

As a plant functional ecologist, I am interested in how plants use resources, such as carbon (C), water and nutrients. I research how plants acquire, allocate and retain those resources, and how they are recycled. I have published on diverse topics within this field, including on plant–animal interactions, invasive species, climate change experiments, algal balls, Christmas trees and carnivorous plants.

A key area of my research is plant silicon (Si), or a term you may be more familiar with, phytoliths. Plants take up silicic acid from the soil solution through their roots and deposit it as silica, predominantly in their leaves, but also in roots, wood and bark. Plants can fill whole cells with silica, deposit it under the leaf cuticle or between cells, and the results can make beautiful shapes. Phytoliths are amorphous silica and when the plant dies, the organic component often decomposes; but phytoliths can persist for a long time — sometimes for millions of years — often as part of soil.

One example of phytoliths is silicified plant stomata — the pores in the leaves that regulate gas exchange. A palaeontologist who is looking at these in the soil sample might focus on using phytolith morphology to provide insight into a past environment, using phytolith abundance; and for species or plant family identification. But when I see images of phytoliths, I ask, "When stomata are completely silicified, and therefore always closed (Fig. 1), what does that do to the plant?" Or more generally, "How do phytoliths, in all their shapes and sizes, function in plants?"

The two fields — palaeontology and ecology — have only recently come together; and while there are some large differences in primary research questions, there is also much information to be shared. As well as phytoliths, there are smaller encrustations of silica in plants that do not persist in the soil, but that are likely important for plant function, and therefore of more interest to me. Hence, in the remainder of this article I will mainly use the terms plant Si or silica rather than phytoliths.

I came across plant Si as an undergraduate. I was writing an archaeology essay as part of my Arts degree — and as I was also doing a Science degree I presumed I could go to the science library and get all the plant Si literature, include it in my archaeology essay and get a good mark. Except there was not much plant Si literature — it just was not there. There were some papers about Si and crops (which I will describe later), but there was almost nothing in the ecology literature.

I found this extraordinary, because in the palaeo literature I was finding papers about palaeoenvironmental reconstruction using phytoliths. For example, Bremond *et al.* (2005) found a strong positive relationship between the percentage of fan-shaped phytoliths and environmental aridity from phytoliths extracted from contemporary soils, which could then be applied to older soils to estimate how arid that landscape was. The palaeontologists had achieved their aim of developing an index to apply to ancient soils; but I had more questions, such as why plants have silicified fan-shaped cells to help them manage arid environments. I could see so much potential in bringing information from the two fields together, and that became the basis of my PhD.

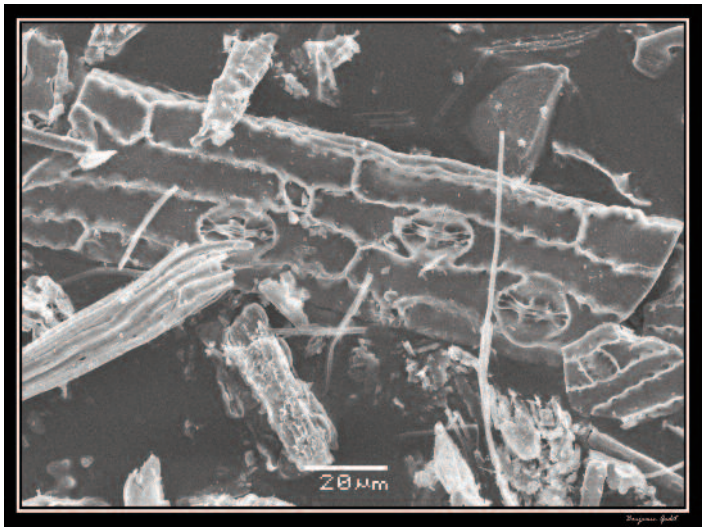


Figure 1 Phytoliths extracted from elephant grass. Whole silicified cells can be seen, including stomata, which normally open and close to release water and take in CO_2 (image by Benjamin Gadet, shared through creative commons licence CC BY-SA 3.0 at: https://commons.wikimedia.org/wiki/File:Phytolithes_observés_au_Microscope_Electronique_à_Balayage_04.jpg).

But first, I want to go back and consider how our understanding of plant Si developed more generally. The global Si cycle was initially considered to be primarily geological, but it is now well established that plants play an important role in Si cycling on Earth. However, in many recent papers about plant Si the same line appears over and over again: "Silicon is the second most abundant element in the Earth's crust" (for example Epstein 1994; Basile-Doelsch 2005; Ma *et al.* 2006; Kuliková *et al.* 2010; and Heckman 2013), as though research into Si needs to be justified. In this article I will discuss research strands relating to plant Si to demonstrate that there is already ample justification for research on plant Si. The three strands are:

1. the role of plants in the global Si cycle;
2. the role of plant Si in past environments; and
3. how plants are able to use Si in the present and future.

Plants and the global Si cycle

When did we first start thinking about phytoliths? Well, like many things biological, we go back to Darwin. Darwin found phytoliths on the HMS *Beagle* in 1835 and he sent them to a German researcher, Christian Gottfried Ehrenbeg, who named them *Phytolitheria*: *phyto* — plant, *lith* — stones.

The next major advance, in my mind, is from much later, when François Bartoli (1983) described how Si cycled through plants — if there are phytoliths forming, then plants must be taking up that Si, and, when plants die, it must be returning to the soil and cycling again. Bartoli was among the first to quantify a local terrestrial cycle. In his diagrams, minerals weather to produce silicic acid in the soil solution. Plants take that up, dropping Si in the leaf litter again, with some Si recycled back into the soil solution through the plants, some leaching away and some precipitating

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out of solution to contribute to the soil and the rock again. By quantifying and comparing Si flux rates in a coniferous forest and in a deciduous forest Bartoli also noticed that cycles in different ecosystems are not the same. The coniferous forest had a faster weathering rate and a faster leaching of silicic acid out of the system. In contrast, the deciduous forest showed a higher turnover: high uptake of Si every year, but also deposition when the leaves fell, leading to fast recycling of Si and little leaching.

John Raven (1983), a plant eco-physiologist, then started thinking about why plants might be using Si; what they could be doing with it. Could they be using it as a structural component; can they use it to deter herbivores? Yes, there was some support for these functions. Then, if plants are using Si in these roles, why are they using Si in roles that are otherwise filled by C?

When identifying which resource to use, costs must be considered. Photosynthesis is an expensive business: generally a leaf must be built, nitrogen acquired, pigments made, and chloroplasts set up — all just to get photosynthesis happening. However, these processes are then lucrative, because the result is fixing C, which fuels much of life on Earth. Silicon, in contrast, is dissolved in the soil solution, and can be taken up with water through roots, making it comparatively cheap. Raven (1983) estimated that acquiring Si was between a tenth and a twentieth of the cost of the same amount of C.

Carbon is a flexible atom for molecules — complex DNA strands, fatty acid chains and all kinds of molecules can be built from C. In contrast, silicon does not naturally form such diverse molecules. Therefore, C can be considered a more expensive resource that is more versatile, while Si is much cheaper but less flexible (Raven 1983).

Emmanuel Epstein was also actively thinking about plant Si around this time, and how much was in plants. He found that plants have 0.1% to 10% of their dry mass as Si (Epstein 1994). That means, when you take all of the water out, some plants are 10% silica. An example of plants with very high-Si contents are the horsetails — you might be familiar with these and know how rough they feel, which is a result of their high-Si content. But all plants have at least some Si in them. The general consensus is that it is not an essential element for plants, but it is very hard to test this because it is difficult to grow plants without Si. However, most plants survive with minimal Si, though for horsetails it does seem essential, for them to maintain their upright structure.

By the mid-1990s, Epstein was arguing that there was ample evidence that Si, when readily available to plants, plays an important role in their growth, mineral nutrition, mechanical strength, and resistance to fungal diseases and adverse environmental conditions. These conclusions were significant, because before Raven's and Epstein's work, the more common view was that plants could not help taking up Si, and deposited it in cells as a waste product. Raven and Epstein drew together compelling arguments that plant Si matters, but these ideas were not incorporated into plant ecology at this time.

There can be a lot of Si in plants and, relative to the other nutrients, Si occurs in macro-nutrient concentrations (rather than micro-nutrient). Compared to the essential macro-nutrients and micro-nutrients, Si concentration in plants is very variable, but it is accumulated by plants in nearly the highest amounts (Epstein 1994). Si accumulation is variable not only across species, but also within a species. This fact is useful because it means it can be manipulated experimentally; but it is also problematic because the large amount of variation means collecting a lot of samples to quantify silica content accurately.

Also, towards the late 1990s, more people looked at Si cycles in different eco-systems. Anne Alexandre and colleagues (1997) quantified Si fluxes in a rainforest in the Congo, to add to the coniferous and deciduous forest data collected by Bartoli. The findings showed Si behaving much like other nutrients plants use, such as nitrogen and phosphorous. Most of the plant-available Si was at the top of the soil profile and decreased down through the profile, adding more weight to the idea that Si is a valuable nutrient for plants. It also shows that silicate weathering, once assumed to be independent of plants, might be driven by plants, because they appear to be using much of the Si available in the soil. The mechanics of this are beyond the scope of this article, but more information is available in the literature (e.g. Cornelis and Delvaux 2016).

Daniel Conley, based in Sweden, separated lithogenic and biogenic Si when looking at Si discharge from terrestrial ecosystems. This meant that when looking at the amount of Si in a river, for example, it was possible to tell whether it had been through a biological system or that it has weathered directly from a mineral substrate (Coney 1997). Importantly, Conley noted that much of the Si in a river had already cycled through a biological system. This was further evidence that it was not just rocks weathering and Si leaching into rivers (and then oceans), but rather plants driving part of this cycle. Silicon deposition into the sea matters, because diatoms, which have a silica structure, are key to productivity in the oceans.

Conley also estimated global Si fluxes. He considered annual plant productivity, the C content of those plants, the C to Si ratios, and thus he started putting numbers on the plant contribution to the global Si cycle. Conley estimated between 60 and 200 terra moles per year of Si is fixed by plants (Conley 2002), an amount similar to how much Si is fixed by diatoms in the ocean. He highlighted that this finding meant potential limits for weathering models, and noted that changes in vegetation communities over time would have had an impact on weathering rates over time.

At the same time, more vegetation Si cycles were being quantified — notably a bamboo forest (Meunier *et al.* 1999). Bamboo is a very high-Si accumulator — with large numbers of phytoliths produced. Comparing all four forest types — deciduous, coniferous, rainforest and bamboo — it was clear that these species were using Si differently, as the fluxes in the different forest types were very different (Conley 2002). In some ecosystems, the main Si pool was the plants themselves, while in others phytoliths accumulated and persisted in the soil, and the rate at which Si moves between these pools was also different among vegetation types.

After looking at Si fluxes from ecosystem scale perspective, researchers began to look at individual species. There were data throughout the literature where Si had been measured in individual species, but Martin Hodson brought these data together in a meta-analysis (Hodson *et al.* 2005). He compiled Si concentration data from 735 species (which is impressive, but only a tiny fraction of total plant species) in plant shoots (above ground parts excluding bark and woody stems and trunks). This data compilation showed that there were high accumulating families such as the grasses and horsetails, and low-Si-accumulating families including brassicas and the rose family. Quantifying the variation

among families was a big advance in the mid-2000s, but we still did not understand what was contributing to this variation in accumulation.

The following year a ground-breaking paper was published, identifying a Si transporter in the roots of rice that actively takes up Si (Ma *et al.* 2006). Presence or absence of these transporters in different plant species accounts in part for the big difference in Si accumulation among species. By making this gene ineffective in a line of rice (the 'knockout' approach), researchers were able to show that without the gene, rice could only take up a small amount of Si. In addition, the knockout plants were weaker and more susceptible to insect damage. Since this first gene encoding an active transporter requiring energy to function was described, a number of other transporters have been identified as well, both active and passive.

Towards the end of the millennium, another key plant Si paper was published, which was a global Si cycle with plants featured front and centre (Struyf *et al.* 2009). Conley's values of 60–200 terra moles per year of plant Si fixation were included and compared to ocean storage, weathering rates and other Si fluxes. This study was published during the early part of my PhD research.

Eric Struyf investigated the impact of vegetation change on Si cycling, i.e. looking beyond ecosystems in a steady state to what happens when an ecosystem was changing (Struyf *et al.* 2010). He used Si export in watersheds and showed that (a) the weathering and uptake is largest for a developing forest, (b) uptake, deposition and recycling are in balance in a mature forest, (c) when the forest is cleared there is less uptake and a much bigger export of Si, and finally (d) in a cultivated area there is a steady cycle again, but one with much smaller fluxes than in the forest. Given these results, Struyf argued that it was necessary to take the human impact on plant Si cycles into account in the global cycle.

Until now I have discussed plants, but not ecology *per se*. Although the references mentioned above have related to agriculture, forests and ecosystems, when I was talking to my plant-ecology colleagues in the 2010s they were often surprised to learn that all plants contained Si. This led me to write and publish my first paper on plant Si. By asking the question, "Is plant ecology more siliceous than we realise?" I could present the argument that Si was an overlooked element in plant ecology (Cooke and Leishman 2011a). I pulled together all the evidence already in the literature, including some that I have outlined here, to argue that there was a resource that plants were using that we had not yet properly appreciated.

Plant Si in past environments

When we look at global cycles, we can measure what happens today, but a better understanding can be obtained by also looking at the past. Many people are familiar with artists' recreations of the Carboniferous landscape (e.g. Fig. 2). When I look at such images, I am immediately struck by the dominance of plants whose relatives today have high-Si content (e.g. horsetails or *Equisetum*) and think that there could have been a lot more Si in Carboniferous vegetation than we see in plants today.

Trembath-Reichert and colleagues (2015) considered the times that different plant groups evolved and whether or not contemporary representatives of these plant groups have Si transporters. They showed that the groups that evolved first, from 500mya, including the liverworts, mosses and lycophytes, were unlikely to have had Si transporters; but that the horsetails, first appearing *c.* 380Ma, probably did have Si transporters. Several groups that appeared even more recently did not have transporters, and excluded Si — such as the cycads, ginkgos and conifers. The angiosperms (or flowering plants), which first appeared from 300Ma, most likely did have Si transporters. Hence, it seems that early plants were able to take up Si, then some lineages evolved to take up large amounts using transporters, while others excluded Si. Hence, "a plastic and ancient capacity for Si accumulation within terrestrial plants" is evident (Trembath-Reichert *et al.* 2015).

Conely and Carey (2015) compared current conditions — in which on average the Si concentration of plants is <2% and the siliceous component in oceans is dominated by diatoms — with the Carboniferous, in which Si concentration of plants might have been 10%, and the sea more dominated by sponges. This work highlighted that we need to consider that the role of plants in the past in driving weathering rates might be very different from today. A word of caution is needed here, however, because while amounts of Si in different groups of plants have been published (e.g. Hodson *et al.* 2005), showing high-Si accumulation in horsetails, mosses and club mosses, the figures are based on only a small amount of data. Recently, however, papers have been published with more data on liverworts (e.g. Thummel *et al.* 2019. Interestingly, Thummel and colleagues report that cleaning samples is integral to obtaining an accurate measure of plant Si, because such plants such as liverworts, can have many Si-rich diatoms attached to them, because they often grow in damp environments. Thus, it is possible that earlier papers were reporting inaccurate results.

Figure 2 An artist impression of a Carboniferous landscape, with giant horsetails (presumably very high in Si) on the right-hand side (image is in public domain, downloaded from: https://en.wikipedia.org/wiki/Carboniferous#/media/File:Meyers_b15_s0272b.jpg).

Plant use of Si today and in the future

Raven (1983) and Epstein (1994) listed a large range of functions for Si in plants, but this was based on small amounts of evidence. The last 15 years has seen an explosion of research in this area and an impressive accumulation of information about how plants use Si.

It has been shown that animals do not really like eating Si in plants. If animals are offered two leaves of the same species, one grown with high amounts of Si available and the other with low-Si availability, the animal will generally choose the lower-Si leaf. Si in plants provides a defence against herbivores. Studies of bank voles by Massey and Hartley (2006) show that when vertebrates eat a high-Si diet they extract less nitrogen from their food. Research on much larger mammals, such as zebras and giraffes, suggests that they have evolved high crowned teeth to manage high-Si diets (e.g. Hummel *et al.* 2010). It has also been shown that if some plants are being badly damaged by herbivores, they respond by taking up more Si (Massey *et al.* 2007). An induced defence, such as that shown by Massey *et al.* implies the defence is costly, because if it were not, then plants would be more likely to express the defence all the time. While Si does seem to be cheaper than C, this work suggests there are still costs associated with plant uptake and use of Si — which is in my view needs further investigation.

Silicon also affects invertebrate herbivores. It has physical effects — the mandibles of army worms are worn down much more quickly on high- versus low-Si diets (Goussain *et al.* 2002). Silicon can reduce the amount of nitrogen invertebrates absorb as well, and to avoid high-Si plants, some butterflies can detect how much Si is in a plant and lay their eggs on lowest-Si plants to give their young the best diet (Reynolds *et al.* 2009).

Silicon affects both vertebrate and invertebrate herbivores, but we are not quite sure how the responses of these two groups to plant silicon is linked over evolutionary time. Caroline Strömberg and colleagues (2016), in a special issue of *Functional Ecology* that I edited in 2016, looked at which periods in evolutionary history there could have been a demand for plants to use Si, as well as when plants evolved to use Si, to see if these coincided. The expectation that had been in the literature was that as the large vertebrates evolved with high-crowned teeth, we should see the evolution of siliceous plants — but no such correlation was found. Instead, Strömberg *et al.* (2016) proposed that the evolution of insects may have driven Si uptake in some plants. Another paper by P. D. Polly came out in 2018, arguing that the spread of Si-rich grasslands in Australia drove evolutionary changes in kangaroo mouth parts. The co-evolution of animals and high-Si plants is an active field of research.

Before I became interested in plant Si, I worked on plant ecological strategies — described by suites of traits such as plant height, seed size and leaf area that correlate with each other. One example is the 'leaf dry mass economic spectrum (Wright *et al.* 2004). The easiest way to describe strategies is to consider leaves at each end of the spectrum. First is a leaf that lives fast and dies young — for example those produced each year on deciduous trees, which are built cheaply and grow quickly, photosynthesise at high rates, and are poorly defended, but are discarded each autumn. An Australian gum leaf, in contrast, is expensive to build (thick, tough, full of tannins) and well defended, but retained for multiple years giving sufficient returns on the investment. I wanted to know if plant Si fitted into this strategy. Knowing that Si accumulated throughout the life of a leaf, I presumed longer-living leaves would accumulate and use more Si than short-lived leaves. But in my research (Cooke and Leishman 2011b) I found the opposite — deciduous leaves accumulate more Si than long-lived leaves. Thinking about this more carefully, it makes sense in terms of costs: a deciduous leaf needs to grow quickly to get through a season, and maybe it can use Si (cheap, but inflexible) for structure and defence, while a long-lived leaf needs more flexibility. This work suggested a trade-off between plant use of Si and C.

I found more evidence of a trade-off in plant defences. At a site in Sydney, where a volcanic diatreme in sandstone has produced adjacent areas of basalt- and sandstone-derived soils, I surveyed the plant defences in the vegetation on each soil type, where the only environmental difference is the soil type, as the climate is the same. I found a negative correlation between Si concentration and the carbon-based defences (phenol and tannin levels in the leaves), which was evidence that plants are investing in Si or C-based defences, but not both (Cooke and Leishman 2012).

I study the role of Si in plants from an ecological perspective, but many other plant Si researchers are more agriculturally focussed because plants use Si to alleviate a huge range of biotic and abiotic stresses, which means Si can be used to increase crop yields in stressed plants (summarised by Ma and Yamaji 2006). Briefly, Si can affect leaf angle to increase canopy photosynthesis, reduce disease and pest damage, and alleviate chemical stresses (e.g. heavy metal or salinity toxicity) and physical stresses (e.g. wind and drought). There are hundreds of studies on the effects of adding Si to single species exposed to a single stress, but representing many species and stresses collectively. I combined these studies in a meta-analysis (Cooke and Leishman 2016), which showed that following Si addition to stressed plants, there are consistent increases in photosynthetic rates, chlorophyll content and biomass, but that oxidative stress markers are reduced (Fig. 3, *opposite*).

A current estimate of annual global plant Si uptake is 84 terra moles, with 35% accounted for by agriculture because several dominant crops are high-accumulating species, such as rice and maize (Carey and Fulweiler 2016). For optimum crop yields, silicon fertiliser is routinely applied to rice in parts of Asia, as it is estimated that half of the rice paddies in China are deficient in Si, because Si is removed when crops are harvested. Roughly 30 million tons of Si fertiliser per year is applied in China. People are changing the way Si cycles in landscapes and researchers have estimated the magnitude of new, significant Si fluxes caused by agriculture (Vandevenne *et al*. 2012).

In future, as atmospheric CO_2 concentration continues to increase, C could become cheaper for plants to acquire. But what does that mean for Si? Data from a Free Air CO_2 Enrichment (FACE) experiment where additional CO_2 is pumped on an ecosystem to predict what might happen in future atmospheric conditions, show that for both developing coniferous forests and evergreen forests, plants did not take up more Si per unit mass, but because treated plants grew bigger in the experiment, they took up more Si overall (Fulweiler *et al.* 2015). Additionally, in a study by Johnson and Hartley (2018), under-elevated CO_2 grasses took up less Si. That might be because there was more CO_2 available, hence plants did not need to have stomates open for as long, and therefore could use water more efficiently. A decrease in Si uptake under higher-atmospheric CO_2 may be a concern,

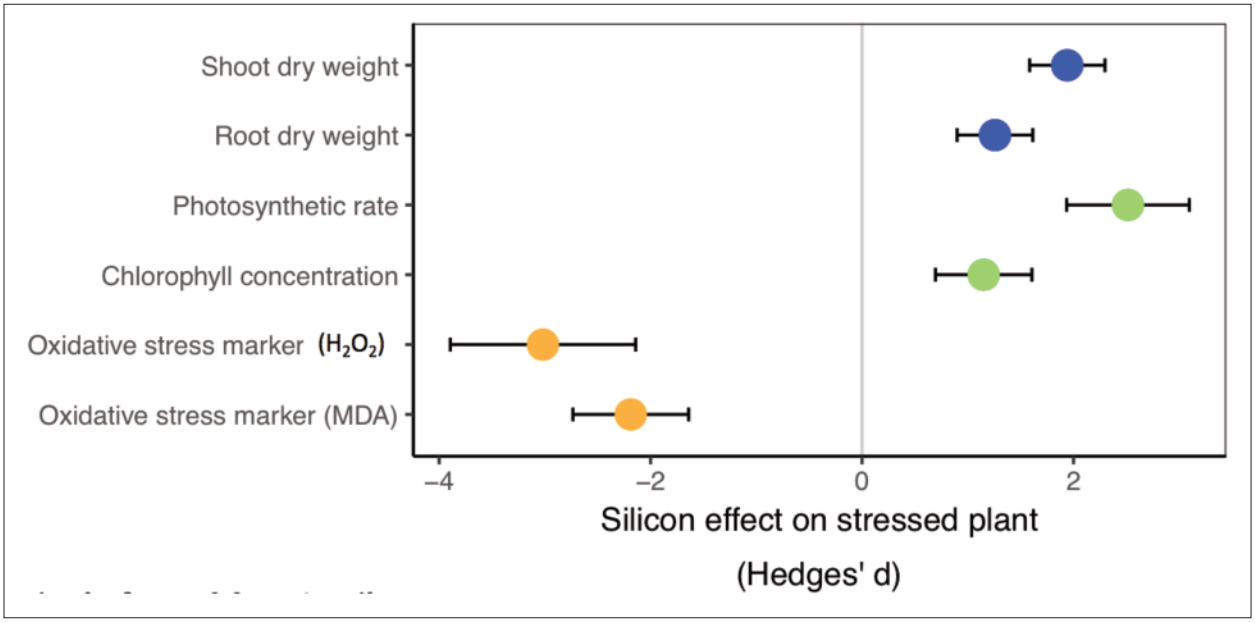

Figure 3 Across diverse species and stressors, Si addition consistently resulted in increased photosynthesis and growth, and reduction in oxidation stress markers (adapted from Cooke et al. *2016). A positive value of Hedge's d indicates that plants supplied with silicon had a higher value for a parameter than plants not supplied with Si and vice versa. Bars are 5–95% confidence intervals and results are considered significant if the confidence intervals so not span zero.*

given the capacity of Si to alleviate a range of stresses that could otherwise help plants manage the impacts of climate change. But research in this area is just beginning, so it is too early to make big deductions.

Conclusions

Now, when I go to conferences, rather than people expressing surprise that plants contain Si, there are sometimes sessions *dedicated* to plant Si. Only five years after that first paper I wrote on plant Si (Cooke and Leishman 2011a), arguing that plant ecology is more siliceous than we realised, I published another paper (Cooke *et al.* 2016) documenting where ecology and plant ecology had better incorporated plant Si since then. My colleagues and I expressed some final thoughts in the 2016 editorial in that issue of *Functional Ecology*: we do not need the statement that Si is the second-most abundant element in the Earth's crust anymore, because we no longer need to justify our interest in Si. It is clear that plant Si matters in the functioning of ecosystems and now ecologists and palaeontologists are taking that on board.

References

Alexandre, A., Meunier, J. D., Colin, F., and Koud, J. M. 1997 'Plant impact on the biogeochemical cycle of Si and related weathering processes'. *Geochim et Cosmochim Acta* **61**, 677–82

Bartoli, F. 1983 'The biogeochemical cycle of Si in two temperate forest ecosystems'. *Ecolog Bull* **35**, 469–76

Basile-Doelsch, I., Meunier, J. D., and Parron, C. 2005 'Another continental pool in the terrestrial Si cycle'. *Nature* **433**(7024), 399

Bremond, L., Alexandre, A., Peyron, O., and Guiot, J. 2005 'Grass water stress estimated from phytoliths in West Africa'. *J Biogeogr* **32**, 311–27

Carey, J. C., and Fulweiler, R. W. 2016 'Human appropriation of biogenic silicon–the increasing role of agriculture'. *Funct Ecol* **30**, 1331–9

Conley, D. J. 1997 'Riverine contribution of biogenic silica to the oceanic silica budget'. *Limnol and Oceanogr* **42**, 774–7

Conley, D. J. 2002 'Terrestrial ecosystems and the global biogeochemical silica cycle'. *Global Biogeochem Cycles* **16**, 68–1

Conley, D. J., and Carey, J. C. 2015 'Biogeochemistry: Silica cycling over geologic time'. *Nature Geosci* **8**, 431

Cornelis, J. T., and Delvaux, B. 2016 'Soil processes drive the biological Si feedback loop'. *Funct Ecol* **30**, 1298–310

Cooke, J., and Leishman, M. R. 2011a 'Is plant ecology more siliceous than we realise?' *Trends Plant Sci* **16**, 61–8

Cooke, J., and Leishman, M. R. 2011b 'Silicon concentration and leaf longevity: is silicon a player in the leaf dry mass spectrum?' *Funct Ecol* **25**, 1181–8

Cooke, J., and Leishman, M. R. 2012 'Trade-offs between foliar silicon and carbon-based defences: evidence from vegetation communities of contrasting soil types'. *Oikos* **121**, 2052–60

Cooke, J., and Leishman, M. R. 2016 'Consistent alleviation of abiotic stress with silicon addition: a meta-analysis'. *Funct Ecol* **30**, 1340–57

Cooke, J., DeGabriel, J. L., and Hartley, S. E. 2016 'The functional ecology of plant Si: geoscience to genes'. *Funct Ecol* **30**, 1270–6

Epstein, E. 1994 'The anomaly of Si in plant biology'. *Proc Nat Acad Sci* **91,11–17**

Fulweiler, R. W., Maguire, T. J., Carey, J. C., and Finzi, A. C. 2015 'Does elevated CO2 alter silica uptake in trees?' *Frontiers Plant Sci* **5**, 793

Goussain, M. M., Moraes, J. C., Carvalho, J. G., Noguiera, N. L., and Rossi, M. L. 2002 'Effect of silicon application on corn plants upon the biological development of the fall armyworm Spodoptera frugiperda (JE Smith)(Lepidoptera: Noctuidae)'. *Neotropic Entomol* **31**, 305–10

Heckman, J., 2013 'Silicon: A beneficial substance'. *Better Crops* **97**, 14–16

Hodson, M. J., White, P. J., Mead, A., and Broadley, M. R. 2005 'Phylogenetic variation in the Si composition of plants'. *Ann Botany* **96**, 1027–46

Hummel, J., Findeisen, E., Südekum, K. H., Ruf, I., Kaiser, T. M., Bucher, M., and Codron, D. 2010 'Another one bites the dust: faecal

silica levels in large herbivores correlate with high-crowned teeth'. *Proc Roy Soc B: Biolog Sci* **278**, 1742–7

Johnson, S. N., and Hartley, S. E. 2018 'Elevated carbon dioxide and warming impact silicon and phenolic□based defences differently in native and exotic grasses. *Global Change Biol* **24**, 3886–96

Kuliková, Z. L., and Lux, A. 2010 'Silicon influence on maize, Zea mays L., hybrids exposed to cadmium treatment'. *Bull Environm Contamin and Toxicol* **85**, 243–50

Ma, J.F., Tamai, K., Yamaji, N., Mitani, N., Konishi, S., Katsuhara, M., Ishiguro, M., Murata, Y. and Yano, M., 2006 'A Si transporter in rice'. *Nature* **440**(7084), 688

Ma, J. F., and Yamaji, N. 2006 'Silicon uptake and accumulation in higher plants'. *Trends Plant Sci* **11**, 392–7

Massey, F. P., and Hartley, S. E. 2006 'Experimental demonstration of the antiherbivore effects of silica in grasses: impacts on foliage digestibility and vole growth rates'. *Proc Roy Soc B: Biolog Sci* **273**, 2299–304

Massey, F. P., Ennos, A. R., and Hartley, S. E. 2007 'Herbivore specific induction of silica-based plant defences'. *Oecologia* **152**, 677–83

Meunier, D. J., Colin, F., and Alarcon, C. 1999 'Biogenic silica storage in soils'. *Geology* **27**, 835–8

Polly, P. D. 2018 'Marsupial responses to global aridification'. *Science* **362**(6410), 25–6

Raven, J. A. 1983 'The transport and function of Si in plants'. Biologic Rev 58, 179–207

Reynolds, O. L., Keeping, M. G., and Meyer, J. H. 2009 'Silicon-augmented resistance of plants to herbivorous insects: a review'. *Ann Applied Biol* **155**, 171–86

Strömberg, C. A., Di Stilio, V. S., and Song, Z. 2016 'Functions of phytoliths in vascular plants: an evolutionary perspective. *Funct Ecol* **30**, 1286–97

Struyf, E., Smis, A., Van Damme, S., Meire, P., and Conley, D. J. 2009 'The global biogeochemical Si cycle'. *Silicon* **1**, 207–13

Struyf, E., Smis, A., Van Damme, S., Garnier, J., Govers, G., Van Wesemael, B., and Vandevenne, F. 2010 'Historical land use change has lowered terrestrial silica mobilization'. *Nature Commun* **1**, 129

Thummel, R. V., Brightly, W. H., and Strömberg, C. A. 2019 'Evolution of phytolith deposition in modern bryophytes, and implications for the fossil record and influence on silica cycle in early land plant evolution'. *New Phytolog* **221**, 2273–85

Trembath-Reichert, E., Wilson, J. P., McGlynn, S. E., and Fischer, W. W. 2015 'Four hundred million years of silica biomineralization in land plants'. *Proc Nat Acad Sci* **112**, 5449–54

Vandevenne, F., Struyf, E., Clymans, W., and Meire, P. 2012 'Agricultural silica harvest: have humans created a new loop in the global silica cycle?' *Frontiers Ecol and Environm* **10**, 243–8

Wright, I. J., Reich, P. B., Westoby, M., Ackerly, D. D., Baruch, Z., Bongers, F., and Flexas, J. 2004 'The worldwide leaf economics spectrum'. *Nature* **428**(6985), 821

First rock from the Sun: the geology of Mercury

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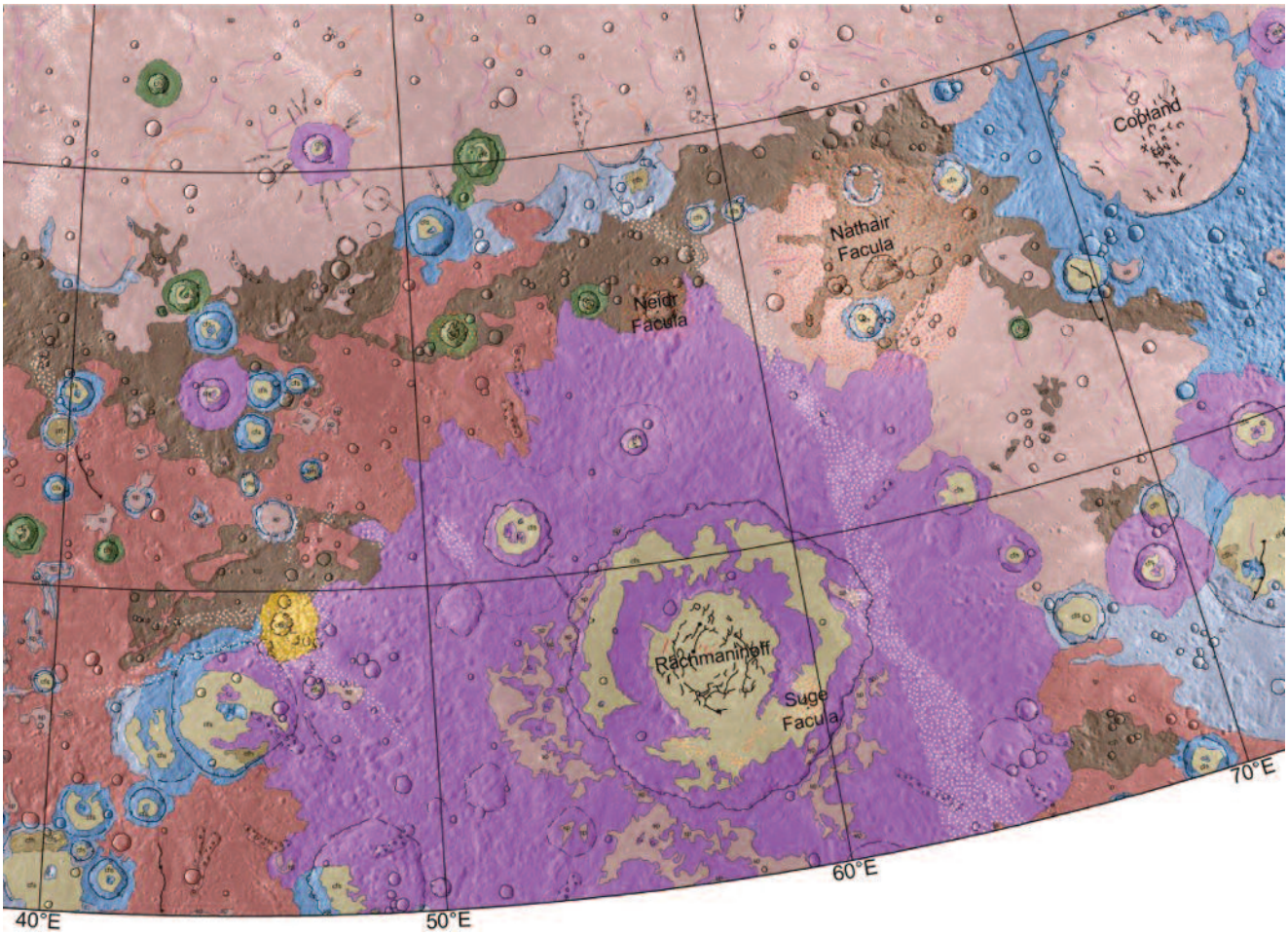

Figure 1 Part of a 1:3 million scale map of the Hokusai quadrangle (H05) of Mercury, extracted from Wright et al. *(2019), from where the whole map can be downloaded (open access). The full quadrangle is 0–-90° E and 22.5°–65°N. Shades of brown are plains of different ages. Yellow, purple, green, dark blue, and light blue distinguish five crater degradation classes, which correlate with relative age.*

Introduction

When I began my career at the OU, mapping in the Oman ophiolite under the supervision of Ian Gass (the founding Professor of Earth Sciences at the OU, and the first OUGS President), I could not have predicted that today I would be supervising my own PhD students making geological maps of large parts of the planet Mercury (Fig. 1). This is because I became involved with the European Space Agency's mission to Mercury, BepiColombo, and am leading ESA's 'Surface & Composition Working Group' for the project. This means that for several years I have been working very closely with colleagues from several other European nations.

BepiColombo

BepiColombo was launched from Kourou, Guiana, on 20 October 2018. After a complicated series of planetary flybys it is due to arrive in orbit about Mercury at the end of 2025. Once there it will release a Japanese orbiter, Mio, into an eccentric orbit optimised for study of Mercury's magnetosphere; and then the European orbiter, called the Mercury Planetary Orbiter or MPO, will be coaxed into a lower and more circular orbit from where it will study primarily the planet's surface (Fig. 2, *overleaf*).

The British-led instrument on MPO is the Mercury Imaging X-ray Spectrometer, MIXS. This is masterminded from Leicester University, but I am one of the Co-Investigators. MIXS will map the distribution of more than a dozen chemical elements across the planet's surface by means of X-ray fluorescence. This is possible because Mercury's airless surface is bathed in solar X-rays that cause X-ray fluorescence from the surface atoms. This is the same principle by which geochemical laboratories measure elemental composition of rock powders, except that they use an artificial X-ray source and have an ideal flat sample to work with rather than an irregular planetary surface. Because the X-ray flux from the Sun varies with time, we have a companion instrument, the Finnish-led Solar Intensity X-ray Spectrometer, SIXS, monitoring the Sun so that we can calibrate our Mercury surface data.

There are several other instruments on MPO, including high-resolution, visible-near IR cameras (great for mapping the terrain), a thermal infrared imaging system (never yet deployed at Mercury, but which should give us a lot of mineralogical information), and a laser altimeter (which together with stereoscopic imaging should give us a superb global topographic map). In addition,

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Figure 2 BepiColombo's MPO as would appear when in orbit about Mercury.

radio tracking of MPO in its low orbit will enable improved mapping of Mercury's gravity field, leading to better constraints on its crustal thickness and how it varies from place to place.

MESSENGER

So with BepiColombo still on its way, how and why do I have students mapping Mercury already? Well, there was a NASA mission called MESSENGER that orbited Mercury from 2011 to 2015. MESSENGER wasn't so well instrumented as BepiColombo, and it had a considerably more eccentric orbit of which the low-point was always at quite a high northern latitude, so that when over the southern hemisphere some instruments provided little or no useable data. Nevertheless, it provided an amazing trove of information about what has turned out to be an absolutely fascinating planet. The geological maps that my PhD students are making are based on MESSENGER data (especially images) and will help to give context to BepiColombo's observations.

The geology of Mercury

For anyone wanting a review of MESSENGER and its findings, the most comprehensive single source is the book edited by Solomon *et al.* (2018), which is fatter and more up to date than my own book (Rothery 2014). There is also a set of invited papers written at an accessible level in the February 2019 issue of *Elements: An International Magazine of Mineralogy, Geochemistry, and Petrology* (Charlier and Namur 2019; Hauck and Johnson 2019; Thomas and Rothery 2019; Nittler and Weider 2019; Cartier and Wood 2019). Here I summarize some of the most interesting aspects of Mercury, from a geological perspective.

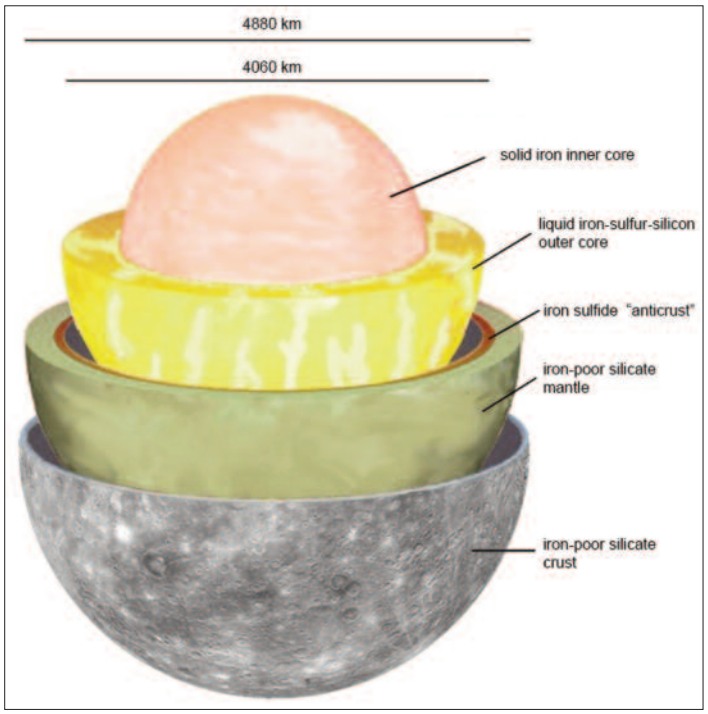
Now that Pluto is no longer classified as a planet, Mercury is the smallest planet in the Solar System. Its mass is only 5.5% that of the Earth (but four and a half times that of the Moon). It is a dense body with a disproportionately large core (Fig. 3), thought to have been stripped of much of its original rocky crust and mantle during a collisional event towards the end of planetary growth. Like the Earth (but unlike Venus, Mars or the Moon), Mercury generates its own magnetic field, which tells us that its core is molten. Solid iron in a planet's core would be too hot (above its 'Curie temperature') to act as a permanent magnet, so to generate a magnetic field there needs to be an electrically conducting fluid, kept moving by a process such as convection, that can act as a self-sustaining dynamo. Models suggest that (like the Earth) only the outer part of Mercury's core is molten, surrounding a solid inner core.

MESSENGER demonstrated, principally by means of its X-ray spectrometer, that Mercury's crust has only about 1–2% of iron by weight, which is much lower than for the Earth or Moon. Iron is scarcely fractionated during partial melting, and so this low iron abundance must apply to Mercury's mantle as well. Almost all of Mercury's iron has evidently been scavenged into its core, presumably because of chemically highly reducing conditions during differentiation that inhibited iron from bonding into silicate minerals.

An important consequence of this is that the silicate magma ocean from which Mercury's crust and mantle solidified was so low in iron that it was not dense enough to enable crystals such as plagioclase to float. In fact, almost all the crystals that formed while the magma ocean was cooling would have sunk. Thus, Mercury never had a 'flotation crust' (a 'primary crust') such as we can see today preserved in the lunar highlands, which are made largely of anorthite (calcium-rich plagioclase). It has been calculated that the only mineral likely to have been buoyant enough to float in Mercury's magma ocean would have been graphite, of which there might have been enough to grow a flotation crust about 200m thick. This has not survived intact, and has been disrupted and covered by a secondary crust emplaced as lava flows and intrusions from magma generated by subsequent partial melting events within the mantle (presumably fuelled by radiogenic heating).

Mercury today is covered by flood basalts, mostly well over three billion years old. The older they are, the more impact craters they have. It is a dark (low albedo) globe, with very little colour variation. However, what colour there is can be exaggerated by image enhancement techniques. Figure 4 *(opposite)* shows equatorial views of two opposite hemispheres in enhanced colour. Younger lavas tend to look redder, and older lavas tend to look bluer (but there are exceptions). The very darkest and bluest areas are thought to be places where the graphite-rich primary crust has been brought to the surface by basin-forming impacts.

Figure 3 The likely internal structure of Mercury (modified from Rothery 2014).



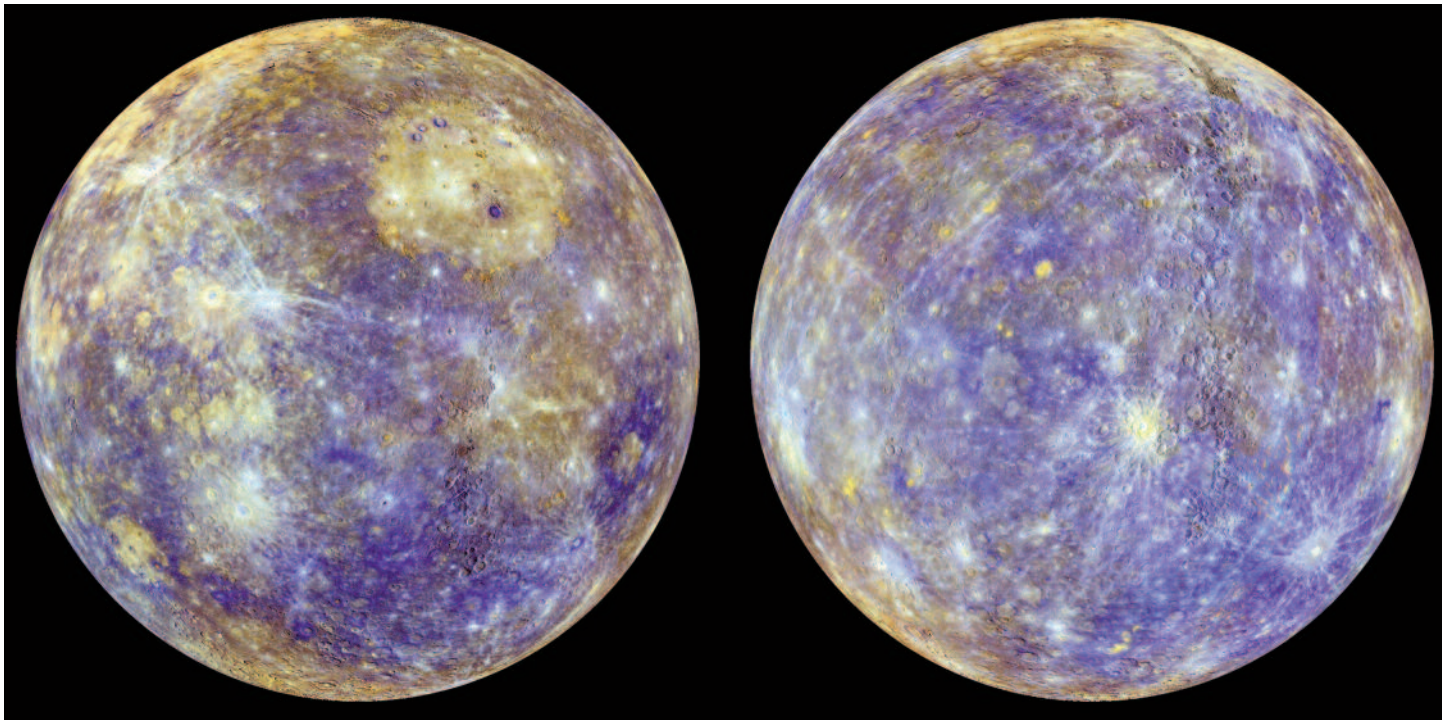


Figure 4 Opposite hemispheres of Mercury, seen in enhanced MESSENGER colour. Left centred at 140°E, right centred at 320°E. This is a standard MESSENGER enhanced colour view (red = 2nd principal component, green = 1st principal component, blue = 433nm divided by 996nm) (NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington).

The north-east part of the left-hand view in Figure 4 includes the 1,550km diameter Caloris Basin, the largest well preserved impact basin on Mercury. Its floor is covered by 'red' lavas, erupted shortly after the basin was formed, which contrast with the generally bluer surrounding terrain.

Figure 5 shows a more detailed view, in similarly enhanced colour, of part of an area near Mercury's north pole that has been named Borealis Planitia. The lower left of the frame contains ancient blue terrain that is heavily cratered. The rest of the frame is occupied by a redder unit that has a lower density of superposed craters. This unit has flooded over the older blue unit, as testified by the partially-flooded pre-existing craters around its edge (example F in Fig. 5), and the 'ghost craters' (G in Fig. 5) that were completely flooded and buried by the red lavas, but whose location can be inferred by the circular wrinkles that developed on the surface as the lavas cooled, contracted and subsided.

No one has yet identified any of the sites from which Mercury's flood basalts were erupted. This is disappointing, but not surprising. We do not see the sources of most of the lunar maria either, because high eruption rates and low viscosities mean that vents

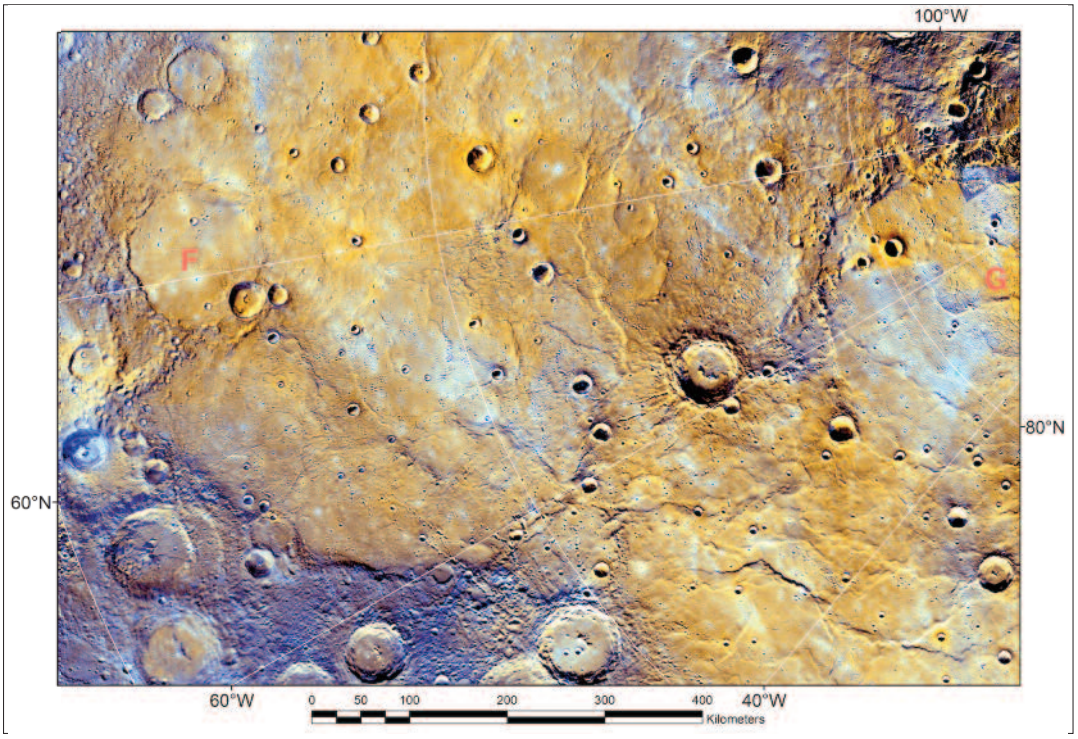


Figure 5 Part of Mercury's Borealis Planitia seen in polar stereographic projection, and containing ample evidence of flooding by lava flows. Longitude is marked at 20° intervals, latitude is marked at 10° intervals. F is within a 140km flooded basin at the southern edge of the plains. G marks two ghost craters whose buried rims are manifested only by wrinkle ridges. This is a standard MESSENGER enhanced colour view (as in Fig. 4), on which the younger volcanic plains appear orange whereas the older terrain to the south (probably also volcanic) appears bluer) (NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institute of Washington).

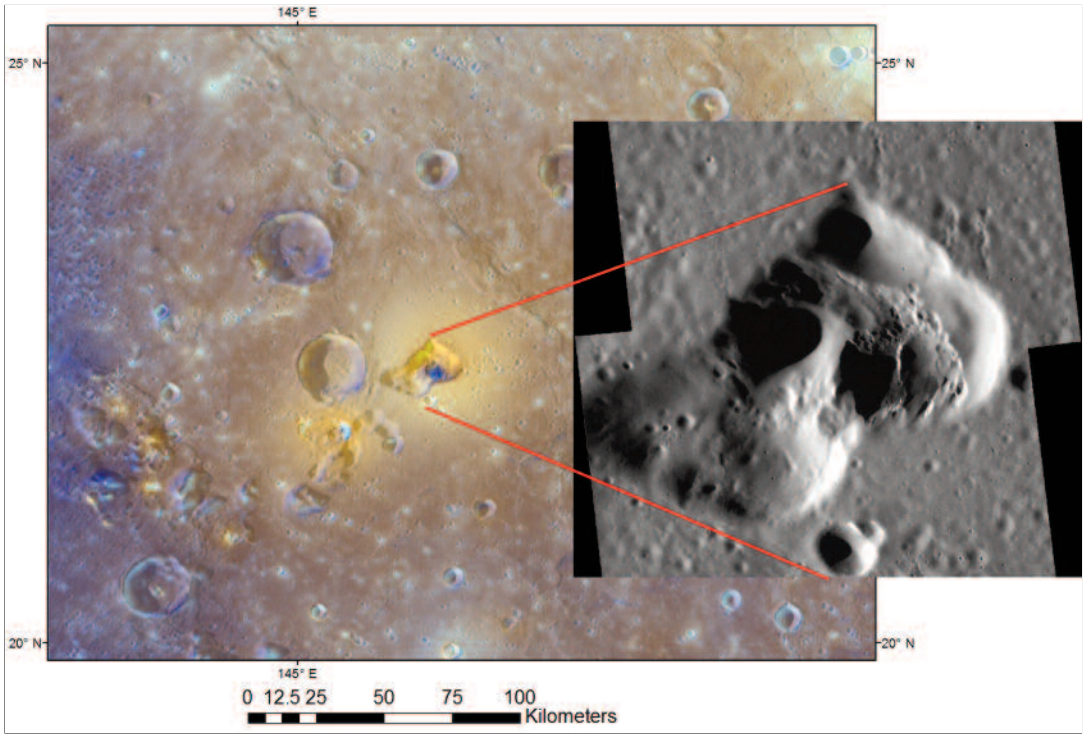


Figure 6 Agwo Facula and the compound volcanic vent at is centre, which is in the south-west of the Caloris basin. Main image: enhanced MESSENGER colour image (as in Figs 4 and 5), centred on the Agwo Facula vent. The facula is the diffuse edged orange spot surrounding the vent (another facula, Abeeso, overlaps it on the south-west). Insert: High-resolution MESSENGER image of the vent, revealing its compound nature. Different impact crater densities and topographic sharpness are revealed in each of the component vents within it (NASA/ Johns Hopkins University Applied Physics Laboratory/ Carnegie Institute of Washington).

become obscured by their own products. However, there are about 200 known sites where explosive volcanic eruptions have burst through the ground on Mercury. These non-circular pits look very different to impact craters, and most are made especially prominent because they are surrounded by a thin but bright red deposit (known as a 'facula') with a diffuse outer edge. Figure 6 shows a classic example of this. The vent is actually a 'compound vent' containing at least nine subsidiary vents within it, attesting to a series of eruptions from almost, but not quite, the same spot over potentially a very long span of time. The relative ages of each subsidiary vent can be deduced from cross-cutting relationships, and age-related changes in surface roughness: first the jagged volcanic morphology becomes muted by regolith-formation and/or deposition of proximal pyroclastic ejecta from younger neighbouring vents, and the number of small superimposed impact craters builds up gradually over time.

These explosive eruptions do not seem to have constructed volcanic edifices of any note; they are essentially holes blasted in the ground. Perhaps the closest analogue on Earth would be a diatreme, except that the ejecta must have dispersed on ballistic trajectories, with no convection because of Mercury's lack of an atmosphere. The deepest part of the vent in Figure 6 is *c.* 1.5km below the level of the terrain beyond the vent, and the record deepest vent elsewhere on Mercury (which is the vent inside Nathair Facula in Fig. 1) has a depth in excess of 3.5km.

It is not clear when Mercury's explosive volcanism was at its peak (many examples might have been buried below flood basalts), but we can tell that at least a few examples that burst through the floors of relatively young impact craters were active within the past billion years.

Mercury's explosive volcanic history tells us something particularly remarkable about Mercury. Explosive volcanic eruptions can occur only if there is plenty of gas available, either in the magma or in the form of crustal volatiles that became mixed into the magma as it neared the surface. To form gas, you need 'volatile elements', and we did not expect an abundance of volatile elements in a planet that formed close to the Sun, and especially in one that had been stripped of much of its original crust as seems to have been the case for Mercury. We do not know the composition of the main gas that drove Mercury's eruptions. Measurements of Mercury's biggest pyroclastic deposit, which is all that MESSENGER could do, suggest that both sulfur and carbon are deficient in the deposit, so perhaps these were lost in the gas (Weider *et al.* 2016). I hope that

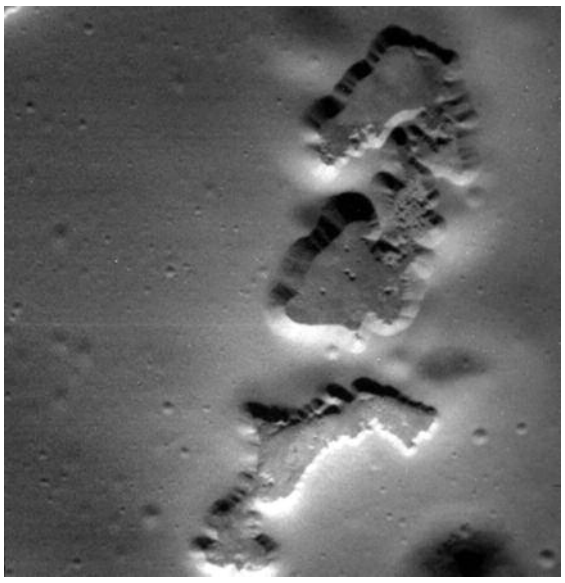


Figure 7 One of MESSENGER's highest-resolution images of hollows, recorded at 3m per pixel. Solar illumination is from the upper left. This area is just 1.5km wide. The older surface, which is peppered with small impact craters, has been stripped away to a depth of about 20m, where hollows have formed. Note that the floors of the hollows must be considerably younger than the surrounding surface, because no impact craters have yet formed there. MESSENGER image 6962760 (NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington).

BepiColombo will be able to obtain many more data points, enabling us to strengthen or revise this hypothesis.

MESSENGER provided some stunning visual evidence of another volatile-related surface processes that had been completely unexpected. There are features that have been dubbed 'hollows' (Fig. 7, *previous page*). Here, in an apparently non-violent, non-explosive, process the top 10–20m of surface has been stripped away, leaving steep-sided, flat-bottomed depressions. This is a much smaller-scale process than the explosive volcanism that excavates the pits. Moreover, it appears to be active today, because there are no clear examples where the floor of a hollow is old enough to have collected an impact crater. BepiColombo is well equipped to determine surface composition inside and outside hollows, and this is just as well because we have very little idea of what is actually going on here. However, surely something volatile is being lost to space. It is unlikely to be simple sublimation (where a substance of fixed composition turns from solid to vapour) and it more likely reflects breaking of chemical bonds. This could occur thermally, or because of solar ultraviolet photons, or because of cosmic ray impacts, or because of micrometeorite sputtering.

In addition to the visual evidence, MESSENGER's geochemical instruments provided some general indicators of Mercury's volatile richness, including several per cent sulfur across the entire globe (assumed to be as sulfides, not elemental sulfur), a high potassium to thorium ratio, and more chlorine and sodium than expected. BepiColombo will be able to pin these down more fully, and with enough spatial resolution to map out variations with geography and age. We may find ourselves forced to the conclusion that the best way to explain Mercury's volatile richness is that it is formed from material that condensed farther out from the Sun than Mercury's present orbit. If so, this would teach us more about planetary migration, a concept that has grown in importance in recent years thanks to both computer modelling of our own Solar System and studies of exoplanetary systems.

I will conclude by mentioning a geologically important aspect of Mercury that does not depend on its volatile richness. This is its global tectonics. Mercury has cooled down (as primordial heat leaked away, and the rate of radiogenic heat production declined) and the ensuing thermal contraction means that its radius has decreased by *c.* 7km over the past 3.5 billion years. Scarp slopes, representing the surface expression of thrust faults, can be mapped in all parts of the globe (e.g. Fig. 8). There is much work still to do deciphering how individual faults are connected, the time-span over which each was active, and their possible roles as pathways for magma ascent and volatile migration.

What next?

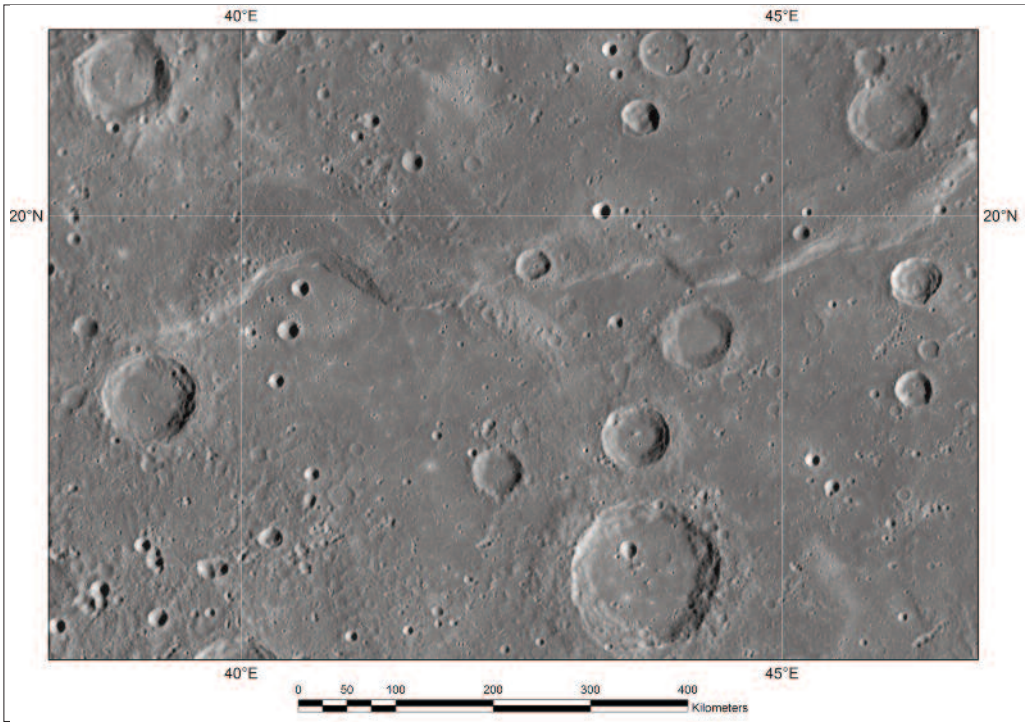
Here at the OU we have so far been responsible for making geological maps of four of the 15 mapping quadrangles into which Mercury is divided. One is already published (Wright *et al.* 2019) and three others are in various states of completion with three current PhD students. Much of this effort has been facilitated thanks to our involvement in PLANMAP, funded by a European Union Horizon 2020 research grant, and I am of course anxious about how this can continue given the idiocy of Brexit. Nevertheless I hope to start another PhD student mapping Mercury's south polar region soon.

Acknowledgements

My Mercury work is currently supported by EU Horizon 2020 grant 776276 'PLANMAP', and I was previously supported by various grants from the Science and Technology Funding Council (STFC) and the UK Space Agency. PhD students are supported by STFC.

(references overleaf)

Figure 8 MESSENGER narrow-angle camera mosaic of an area within the Derain quadrangle (cylindrical projection). An east–west stepped fault scarp (Calypso Rupes) cuts across smooth plains near 20°N. Note the locally-reduced crater density of some patches sharply-bounded by the downthrown (southern) side of the fault suggesting relatively recent ponding of small episodes of topographically constrained lava effusion, especially 40-41°E and 44°E. Note also the ubiquity of 20km flooded craters except close to the southern (downthrown) side of the fault, where ponding would naturally be thickest, completely burying such craters (NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institute of Washington).



References

Cartier, C., and Wood, B. J. 2019 'The role of reducing conditions in building Mercury'. *Elements: An Internat Mag Mineral, Geochem, and Petrol* **15**, 39–45

Charlier, B., and Namur, O. 2019 'The origin and differentiation of planet Mercury'. *Elements: An Internat Mag Mineral, Geochem, and Petrol* **15**, 9–14

Hauck, S. A., and Johnson, C. L. 2019 'Mercury: Inside the Iron Planet'. *Elements: An Internat Mag Mineral, Geochem, and Petrol* **15**, 21–6

Nittler, L. R., and Weider, S. Z. 2019 'The surface composition of Mercury'. *Elements: An Internat Mag Mineral, Geochem, and Petrol* **15**, 33–8

Rothery, D. A. 2014 *Planet Mercury: from Pale Pink Dot to Dynamic World.* Springer

Solomon, S. C., Nittler, L.R., and Anderson, B.J. (eds) 2018 *Mercury: The View after MESSENGER* (Vol. 21). Cambridge UP

Thomas, R. J., and Rothery, D. A. 2019 'Volcanism on Mercury'. *Elements: An Internat Mag Mineral, Geochem, and Petrol* **15**, 27–32

Weider, S. Z., Nittler, L. R., Murchie, S. L., Peplowski, P. N., McCoy, T. J., Kerber, L., Klimczak, C., Ernst, C. M., Goudge, T. A., Starr, R. D., and Izenberg, N. R. 2016 'Evidence from MESSENGER for sulfur- and carbon-driven explosive volcanism on Mercury'. *Geophys Res Lett* **43**, 3653–61

Wright, J., Rothery, D. A., Balme, M. R., and Conway, S. J. 2019 'Geology of the Hokusai quadrangle (H05), Mercury'. *J Maps* **15**, 509–20

Searching for Martians in sulphate-rich lakes on Earth

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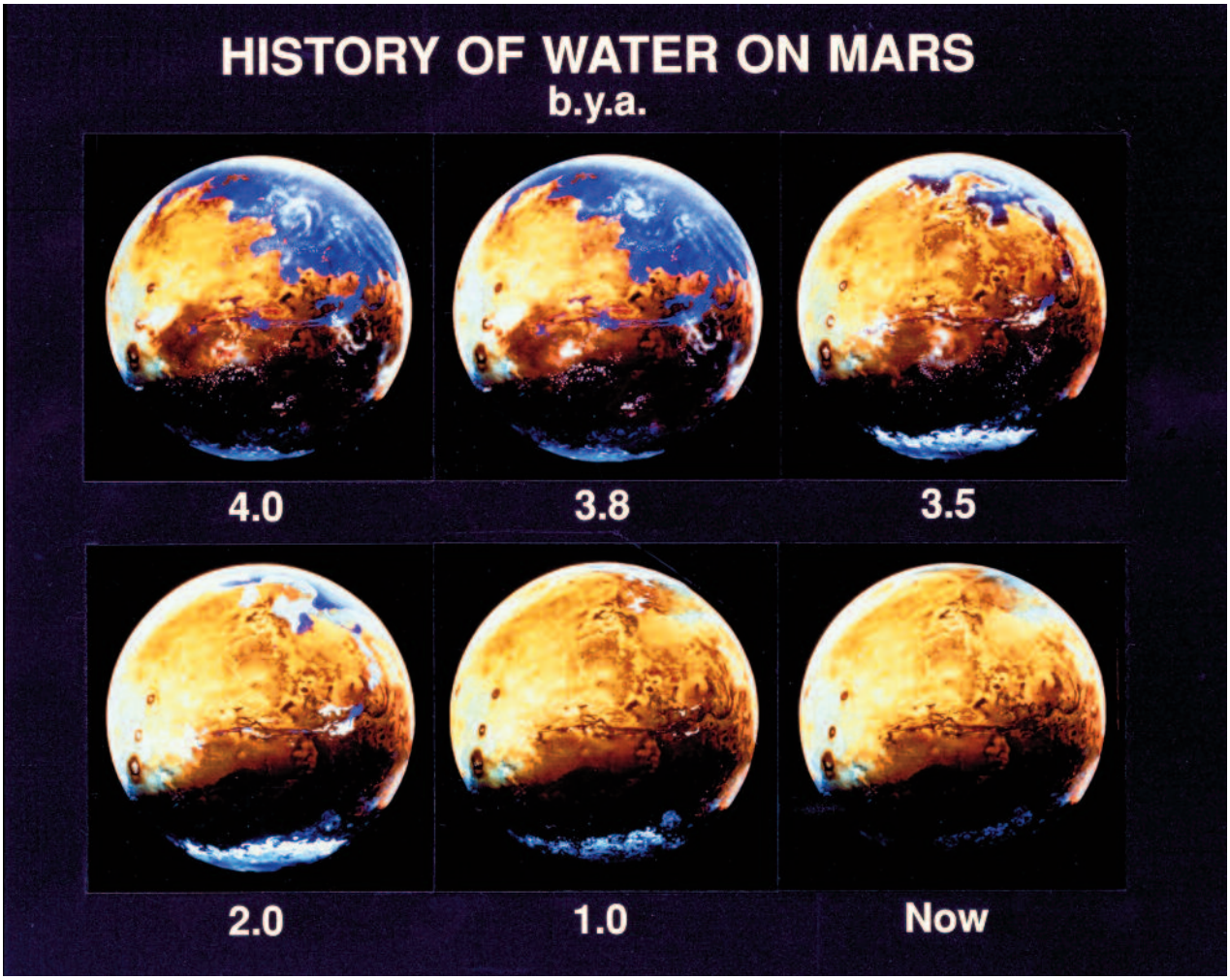

Figure 1 Progressive water loss on Mars (credit: NASA).

One of the questions that has always haunted the human mind is: "Are we alone in the Universe?" On the endeavour to answer this question, since the 1960s, there has been a continuous effort to try to find life elsewhere (Dick and Strick 2005). But the first question that would need addressing is: "What is life?"

A quick search on Google says that life is: "the condition that distinguishes animals and plants from inorganic matter, including the capacity for growth, reproduction, functional activity and continual change preceding death". Some other example definitions would be Schrodinger's, who said: "that which resists decaying to disorder and equilibrium"; NASA's: "a self-sustaining chemical system capable of Darwinian evolution"; and Aristotle's: "by life, I mean self-nourishment, growth and decay".

Some common concepts arise from these definitions: energy, growth, and decay. The energy used by life organisms derives from reduction-oxidation chemical reactions, in which electrons are transferred from one chemical (it gets oxidised) to another (which gets reduced) (Nixon *et al.* 2013). This process requires the presence of oxidised and reduced molecules in order for life to exist. There are certain elements that are vital, such as carbon, nitrogen, hydrogen, sulphur, oxygen and phosphorus, which form the building blocks of life (Des Marais *et al.* 2003; Lal 2008).

On the search for life, research focuses on finding places in which the aforementioned requites are met. In the Solar System there are some bodies that are likely to present conditions that could be conducive for life, such as icy moons (e.g. Enceladus, Titan, Europa), or Mars (Des Marais *et al.* 2003). Life on Mars has populated the human imagination for more than 100 years. The first reference to life on Mars in literature was in *War of the Worlds* by H. G. Wells, in which he described Martians as a very war-like civilisation. It was not until Ray Bradbury wrote his *Martian Chronicles* that Martians were described as 'little green men', a cliché that has been perpetuated and of which there is a plethora of examples, e.g. Marvin the Martian, created by Chuck Jones for Looney Tunes; or in the movie, *Mars Attacks* by Tim Burton (Source: https://www.telegraph.co.uk/culture/culture-news/11297007/life-on-mars-in-popular-culture.html).

In order to answer the question that David Bowie asked in 1983 in his song *Is there life on Mars?*, we need to answer first if life could be, or could have been possible on Mars. Although currently harsh, the conditions on Mars in the past were much more benign (Nixon *et al.* 2013). Plenty of evidence proves a wetter martian past (Carr and Head III 2010; Mangold *et al.* 2012) (Fig. 1). Geomorphological features evidence the presence or

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rivers and deltas (Baker 2006; Martín-Torres *et al.* 2015; Rapin *et al.* 2019), and chemical analysis of the martian surface showed a high abundance (20–30%) of sulphate evaporitic deposits (Martín-Torres *et al.* 2015; Vaniman *et al.* 2004). In order to have such an amount of liquid water, Mars should have had a thicker atmosphere. Under extreme conditions, such as the ones Mars presents today, simple life forms, such as microorganisms, are more likely to thrive. Although not as abundant in pop culture, films such as *Life* has explored the possibility of martian microbial life.

The geochemistry has shown the presence of reduced and oxidised substances, which on Earth are known to be substrates for microbial metabolism (Nixon *et al.* 2013). Examples are olivine containing Fe^{+2}, which then can be oxidised to Fe^{+3} by iron oxidisers (FeOB); and sulphates, which can be reduced to H_2S, by sulphate-reducing bacteria (SRB) (Price *et al.* 2018). Serpentinisation reactions that might occur under the martian subsurface can produce H_2 (Oze and Sharma 2005), which subsequently can be used by hydrogenotrophic bacteria archaea; and the martian atmosphere contains CO_2 and CO, which can be used to fix to organic matter (Nixon *et al.* 2013).

Biosignatures are substances (such as molecules, isotopes, minerals) that are derived from biological activity (Fujii *et al.* 2018; Grenfell 2017; Schwieterman *et al.* 2018). Detecting biosignatures provides fundamental information at the time of deciding where to search for extraterrestrial life. One example of biosignature is methane, which on Earth is mostly produced (90%) by microorganisms called methanogenic archaea (Keppler and Röckmann 2007). Although controversial, methane has been detected on Mars, both by rovers and orbiters (Korablev *et al.* 2019; Witze 2019).

Abiotic processes, such as hydrocarbon fragmentation, or geochemical reactions, can also lead to the formation of methane (Etiope and Sherwood Lollar 2013). Nevertheless, on Earth, there are two ways to differentiate whether the origin of methane is biological or abiotic. The first method is the isotopic composition of methane. Microbial metabolism shows a higher affinity towards lighter isotopes, which yields enriched methane containing ^{12}C and ^{1}H (Etiope and Sherwood Lollar 2013). The other important differentiating method is the methane/ethane ratio. Microbial methanogenic activity is highly specific, which results in methane/ethane ratios of >1,000, whereas if methane is a product of geochemical or thermogenic processes, the ratio is lower (<50) (Tazaz *et al.* 2013).

After Mars lost its atmosphere and subsequently began to lose its water on the surface, water bodies should have been progressively enriched in salts, such as sulphates (Rapin *et al.* 2019) (Fig. 2). Historically sulphate has been regarded as an inhibitor for biological methanogenesis (Abram and Nedwell 1978; Acharya *et al.* 2008). This inhibition is because the first two described methanogenic routes use CO_2 and hydrogen or acetate as substrates. Nevertheless, in sulphate-rich environments, sulphate-reducing bacteria (SRB) proliferate and out-compete methanogenic archaea for the same substrates. In recent years, a third route, called methylotrophic methanogenesis has been described, in which molecules such as methylated amines or dimethylsulphate can be utilised (Costa and Leigh 2014).

In order to identify potential metabolisms that would be or have been viable on Mars, environments with shared conditions need to be assessed on Earth. $MgSO_4$-rich materials are abundant in the interior lakes of the Interior Plateau in British Columbia — for example Basque Lake — with a sulphate-concentration of *c*. 34% (Pontefract *et al.* 2017; Renaut 1994, 1990; Renaut and Long 1989; Waynenesbitt 1990) (Fig. 3, *opposite*). Preliminary *in situ* measurements indicated that methane accumulates within the sediment layer, and upon disturbance, is released into the atmosphere.

Sediment incubations with artificial lake water showed a predominance of methylotrophic methanogenesis, evidenced by accumulation of methane in the closed culture bottles of up to 15% after four months in cultures amended with 50 minimolars (mM) trimethylamine. Samples amended with 50mM acetate or incubated with $CO_2 + H_2$ in the bottle headspace produced negligible amounts of methane, even after four months.

These results lead to the question of what the origin of the trimethylamine is.

High salinity can be detrimental for microbial survival. In order to survive, microorganisms accumulate molecules in their cytoplasm, preventing environmental ions to reach the interior of the cells (compatible solutes) (Empadinhas and da Costa 2008; Roberts 2005). Among these compatible solutes, betaine and choline, play important roles (Boniolo *et al.* 2009). Some of the microorganisms identified from DNA extracted from sediment can accumulate the aforementioned compatible solutes. Cytoplasm content is released to the surrounding sediment upon bacterial death. Both choline and betaine can be enzymatically degraded to trimethylamine (Craciun and Balskus 2012; Lidbury *et al.* 2015) by microorganisms such as *Desulfovibrio* (Craciun and Balskus 2012), which was detected among the DNA sequences recovered from the sediment in the Canadian sulphate-rich lakes that were analysed.

Canadian sulphate-rich lakes constitute a good analogue for an ancient and wetter Mars. Detectable methane was measured *in situ* in Basque Lake, and associated with disturbance of sediment. Incubation of sediment with different substrates for methanogenesis only showed positive results for methylotrophic methanogenesis. Substrates for methane production following this pathway would derive from the decomposition of compatible solutes.

This research into the potential for extraterrestrial life can help us focus on specific environments elsewhere with the right geochemistry and other factors for possible life beyond Earth.

Figure 2 Magnesium sulphate deposits in Gale Crater (marked with red arrows) (https://www.nature.com/articles/s41561-019-0458-8.pdf).

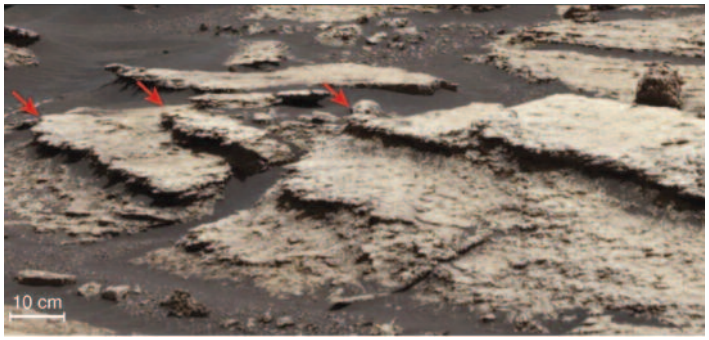

Figure 3 Basque Lake #2 in the Inner Plateau, British Columbia, Canada (Alex Pontefract).

References

Abram, J. W., and Nedwell, D. B. 1978 'Inhibition of methanogenesis by sulphate reducing bacteria competing for transferred hydrogen'. *Archives Microbiol* **117**, 89–92

Acharya, B. K., Mohana, S., and Madamwar, D. 2008 'Anaerobic treatment of distillery spent wash–a study on upflow anaerobic fixed film bioreactor'. *Bioresource Technol* **99**, 4621–6

Baker, V. R. 2006 'Geomorphological evidence for water on Mars'. *Elements* **2**, 139–43; doi.org/10.2113/gselements.2.3.139

Boniolo, F. S., Rodrigues, R. C., Delatorre, E. O., Da Silveira, M. M., Flores, V. M. Q., and Berbert-Molina, M. A. 2009 'Glycine betaine enhances growth of nitrogen-fixing bacteria Gluconacetobacter diazotrophicus PAL5 under saline stress conditions'. *Current microbiol* **59**, 593–9

Carr, M. H., and Head III, J. W. 2010 'Geologic history of Mars'. *Earth Planet Sci Lett* **294**, 185–203

Costa, K. C., and Leigh, J. A. 2014 'Metabolic versatility in methanogens'. *Current Opinion Biotechnol* **29**, 70–5

Craciun, S., and Balskus, E. P. 2012 'Microbial conversion of choline to trimethylamine requires a glycyl radical enzyme'. *Proc Nat Acad Sci* **109**, 21307–12

Des Marais, D. J., Allamandola, L. J., Benner, S. A., Boss, A. P., Deamer, D., Falkowski, P. G., Farmer, J. D., Hedges, S. B., Jakosky, B. M., and Knoll, A. H. 2003 'The NASA astrobiology roadmap'. *Astrobiol* **3**, 219–35

Dick, S. J., and Strick, J. E. 2005 'The living universe: NASA and the development of astrobiology'. *J Hist Biol* **38**, 386–7

Empadinhas, N., and da Costa, M. S. 2008 'Osmoadaptation mechanisms in prokaryotes: distribution of compatible solutes'. *Int Microbiol* **11**, 151–61

Etiope, G., and Sherwood Lollar, B. 2013 'Abiotic methane on Earth'. *Rev Geophys* **51**, 276–99

Fujii, Y., Angerhausen, D., Deitrick, R., Domagal-Goldman, S., Grenfell, J. L., Hori, Y., Kane, S. R., Pallé, E., Rauer, H., Siegler, N., Stapelfeldt, K., and Stevenson, K. B. 2018 'Exoplanet biosignatures: observational prospects'. *Astrobiol* **18**, 739–78; doi.org/10.1089/ast.2017.1733

Grenfell, J. L. 2017 'A review of exoplanetary biosignatures'. *Physics Reps* **713**, 1–17; doi.org/10.1016/j.physrep.2017.08.003

Keppler, F., and Röckmann, T. 2007 'Methane, plants and climate change'. *Sci Amer* **296** (2), 52–7

Korablev, O., Vandaele, A. C., Montmessin, F., Fedorova, A. A., Trokhimovskiy, A., Forget, F., Lefèvre, F., Daerden, F., Thomas, I. R., and Trompet, L. 2019 'No detection of methane on Mars from early ExoMars Trace Gas Orbiter observations'. *Nature* **568**, 517

Lal, A. K. 2008 'Origin of life'. *Astrophys Space Sci* **317**, 267–78

Lidbury, I. D., Murrell, J. C., and Chen, Y. 2015 'Trimethylamine and trimethylamine N-oxide are supplementary energy sources for a marine heterotrophic bacterium: implications for marine carbon and nitrogen cyclin'. *ISME J* **9**, 760–9

Mangold, N., Carter, J., Poulet, F., Dehouck, E., Ansan, V., and Loizeau, D. 2012 'Late Hesperian aqueous alteration at Majuro Crater, Mars'. *Planet Space Sci* **72**, 18–30

Martín-Torres, F. J., Zorzano, M.-P., Valentín-Serrano, P., Harri, A.-M., Genzer, M., Kemppinen, O., Rivera-Valentin, E. G., Jun, I., Wray, J., Madsen, M. B., and others 2015 'Transient liquid water and water activity at Gale Crater on Mars'. *Nature Geosci* **8**, 357

Nixon, S., Cousins, C. R., and Cockell, C. 2013 'Plausible microbial metabolisms on Mars'. *Astron Geophys* **54**, 13–16

Oze, C., and Sharma, M. 2005 'Have olivine, will gas: serpentinization and the abiogenic production of methane on Mars'. *Geophys Res Lett* **32**, 1–4

Pontefract, A., Zhu, T. F., Walker, V. K., Hepburn, H., Lui, C., Zuber, M. T., Ruvkun, G., and Carr, C. E. 2017 'Microbial diversity in a hypersaline sulfate lake: a terrestrial analog of ancient Mars'. *Frontiers Microbiol* **8**; doi.org/10.3389/fmicb.2017.01819

Price, A., Pearson, V. K., Schwenzer, S. P., Miot, J., and Olsson-Francis, K. 2018 'Nitrate-dependent iron oxidation: a potential Mars metabolism'. *Frontiers Microbio* **9**, 513; doi.org/10.3389/fmicb.2018.00513

Rapin, W., Ehlmann, B., Dromart, G., Schieber, J., Thomas, N., Fischer, W., Fox, V., Stein, N., Nachon, M., and Clark, B. 2019 'An interval of high salinity in ancient Gale Crater Lake on Mars'. *Nature Geosci* **12**, 889–95

Renaut, R. W. 1994 'Carbonate and evaporite sedimentation at Clinton Lake, British Columbia, Canada'. *Geol Soc Amer Spec Pap.* Geol Soc Amer, 49–68; doi.org/10.1130/SPE289-p49

Renaut, R. W. 1990 'Recent carbonate sedimentation and brine evolution in the saline lake basins of the Cariboo Plateau, British Columbia, Canada'. *Hydrobiol* **197**, 15

Renaut, R. W., and Long, P. R. 1989 'Sedimentology of the saline lakes of the Cariboo Plateau, Interior British Columbia, Canada'. *Sediment Geol* **64**, 239–64

Roberts, M. F. 2005 'Organic compatible solutes of halotolerant and halophilic microorganisms'. *Saline Systems* **1**, 5

Schwieterman, E. W., Kiang, N. Y., Parenteau, M. N., Harman, C. E., DasSarma, S., Fisher, T. M., Arney, G. N., Hartnett, H. E., Reinhard, C. T., Olson, S. L., Meadows, V. S., Cockell, C. S., Walker, S. I., Grenfell, J. L., Hegde, S., Rugheimer, S., Hu, R., and Lyons, T. W. 2018 'Exoplanet biosignatures: a review of remotely detectable signs of life'. *Astrobiol* **18**, 663–708; doi.org/10.1089/ast.2017.1729

Tazaz, A. M., Bebout, B. M., Kelley, C. A., Poole, J., and Chanton, J. P. 2013 'Redefining the isotopic boundaries of biogenic methane: methane from endoevaporites'. *Icarus* **224**, 268–75; doi.org/10.1016/j.icarus.2012.06.008

Vaniman, D. T., Bish, D. L., Chipera, S. J., Fialips, C. I., William Carey, J., and Feldman, W. C. 2004 'Magnesium sulphate salts and the history of water on Mars'. *Nature* **431**, 663–5; doi.org/10.1038/nature02973

Waynenesbitt, H. 1990 'Groundwater evolution, authigenic carbonates and sulphates, of the Basque Lake No. 2 Basin, Canada'. *Fluid-mineral Interactions* **18**, 355–71

Witze, A. 2019 'Mars rover detects "excitingly huge" methane spike'. *Nature News*; doi.org/10.1038/d41586-019-01981-2

Symposium summing up

OUGS President Dr Susanne Schwenzer (with editorial additions in [ ])

So, now comes the hardest part, because summing up an OUGS Symposium, as a President, is a 'mission impossible' — We have had two days, three days, as you wanted, packed full of activities, of talks, of workshops, of walks. We've heard so many things, topics, information — you saw how many people were involved, too. We had more than 150 participants here — it is a big event and it is an interesting event. Every time, I have attended an OUGS Symposium, I learned a lot, and this time I learned a lot as well! Although, this time, I didn't always have time to pay attention because the OU, as you know, is my home turf, and so if something goes wrong somewhere, then home turf people are required. But again, I couldn't have done it without the helpers who are sitting there and probably don't want me to mention them yet again. (I just got a stern look!) But I do it anyway: Many thanks to everyone, who helped make this symposium the success it was. I am standing here summarizing the days — days, which would have been impossible to have without all the help to make it happen!

Right, so what did we learn? To start the symposium off, we were greeted by Professor Rick Holliman, who compared us to the work of Mary Anning. And I think, the more I thought about this, it is actually a very good comparison. And that's probably an insight that had to come from someone who isn't in our field. Rick is a professor of Engaged Research; thus, it's coming from someone who looks at scientific engagement and how science works in an everyday context, and how science interacts with the world outside the laboratories. Rick studies how advances are made — at that interaction between the laboratories that devise the equations and the graphs and the outside world, and how this translates to each other.

After Professor Holliman's opening address to Symposium, a talk by Dr Marcus Badger followed. He demonstrated something very important: The Earth revolves around the President, right?

I am joking here…

Well, that aside, he spoke about a very serious topic, and that's the rising CO_2 level in our atmosphere. He made it very clear how vast the difference is between what is happening since the 1950s, and what has happened in Earth's history before; and how we might want to think about it and prepare for it. Yet he gave an engaging talk that I very, very much enjoyed. I was always waiting that at the end of his talk he might actually drown that cow on our Symposium poster, but he refrained from it because I don't think he could have stayed in Milton Keynes if he had drowned Milton Keynes' cows.

He introduced the topic by talking about ice and sediment cores, to not only study the most recent time, but also to be able to study atmospheric chemistry further back in time. That's possible using these cores, as we heard again on the final day.

On Saturday morning we abandoned Earth for a while and ventured out about as far as you possibly can get into the Solar System. And actually on Sunday we came full circle, making a fly-by very close to the Sun to go out to Mars again and, in your imagination, back out to the exoplanets. But I will get to that later.

"The Earth revolves around the President, right?"

We started the Saturday with Professor Carole Haswell and the exoplanets. She spoke mostly about a recent discovery that has been made, and that was published in Science. This paper was published, and all the press articles came out at that time, too, just when I was looking for speakers. Therefore, Carole was actually the first colleague I called and said, "Oh, are you happy to talk about this?" and she just said, "There's only one question, when is it? Do I have a hole in my schedule?" — and she agreed right away. Carole also taught us a very important lesson: Does anyone of you now remember that spacecraft that discovered the first exoplanet? "COROT-7" That's brilliant! Yes you do! [A member of the audience did know!] Because you've now heard about it, and it's been put in context. But it's taught us an important lesson: how important it is to actually speak about these things, and name them and put them upon the big screen so people can remember.

But we also learned how important it is for us as geologists to understand that we are really needed out there. There are rocky worlds out there. Carole mentioned minerals that are unknown to her, such as forsterite, pyroxene, feldspar. So, we [geologists] can help with that, right? Can we? [The audience agreed.] Good! So, we will love those that she calls 'the wild and wacky', and the rocky ones. So, I think I'll stick with the rocky ones for the moment.

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And the 'wild and wacky worlds' were the two asteroids that Dr Ben Rozitis introduced us to. I didn't know that that spinning-top toy would actually be important in science one day. It probably was when I played with it, but, how ignorant was I?

Now, we learned how rubble-pile asteroids work — and with really good animations he showed us that we are missing some moons where we are currently having spacecraft — at the two asteroids Bennu and Ryugu. He talked about two different space missions, one by NASA and one by JAXA (Japan Aerospace Exploration Agency). Ben also introduced us to sampling devices, which he called, things such as a 'space vacuum cleaner'; and he didn't explain why that would work in the vacuum of space. And then there was the space 'pellet gun' — sounds a bit more violent to me.

Sampling is tricky, and it's important, because we know from the Apollo samples how important it is to come back with samples that just 'keep giving'. Returned samples keep giving because our technology and analytical instruments evolve and evolve. What could be done on the Apollo samples at the time of Apollo was a lot less than what can be done today; and what can be done today is a lot less than what we will be able to investigate with these samples 50 years from now. And remember, Apollo is just 50 years ago, just a few seconds ago in cosmic or geologic timescales!

Now, we learned a lot about Bennu and ejecting particles and moons that should have formed but haven't, or maybe they got lost. We also learned a lot about spacecraft and how to navigate around an asteroid. We also learned that you actually have to go hide your spacecraft when you shoot a pellet at an asteroid, because in very low gravity that asteroid will 'fire back', and will destroy your spacecraft unless you are hiding it. But, they strategically placed a camera and that actually captured the event.

Our next speaker was Dr Tom Barrett, who gave us a whistle-stop tour to volatiles in the Solar System. Of course, you can't talk about volatiles without also talking about asteroids and near-Earth asteroids, and he spoke about the Chelyabinsk meteorite, which hit the Earth on 15 February 2013. Tom showed with impressive pictures from car dash-cams and shattered windows what actually happens when a meteorite like this hits us. Tom also explained what he does, if you bring him a meteorite, or something you think is a meteorite, and how he makes that decision, whether it's a meteorite or not, with confidence and accuracy. Of course, the answer is always 'isotopes'. Tom loves oxygen isotopes, I love noble gases and their isotopes, and they both do the job.

So, there is a lot of water in these meteorites, but we learned that some of them are drier than 'bone dry', because our bones are not actually that dry. They [our bones] have up to 10% of water if I remember right. Thank you for the 'thumbs-up' back there! So, Tom was talking about the Moon and the water on the Moon and minerals that shouldn't have any water, but we can detect just a little trace of water. This is one of the advancements in analytical techniques that we can now detect that little trace of water and distinguish it from water that could have been a source on Earth, which we couldn't when the Apollo samples first were brought back.

Tom also mentioned that this year NASA is opening one of the Apollo crates that had never been opened before, and will make the samples available for study. So we still have pristine samples in boxes that were sealed on the Moon, and there are more than this one. Of course, there was a long debate about the crate to be opened, and the procedures of how to do it. There was a proper scientific selection process to decide which crates to open; a scientific consortium also decided which project will sample first from that crate. Actually, a former OU student is part of the group of investigators — not quite the most boring day job… let me put it that way. And of course an amazing achievement for that student and for the OU!

So, after our excursion to the Moon, we returned to Earth — well not quite. We returned to Earth with Professor Nigel Harris to learn how mountain ranges form. His talk centred around the mechanisms that formed the Himalayas, how big volcanoes build up, focusing on how volcanoes get big, or not, and why.

And, then Nigel took us back out to space, and made the point that there are many planets, but that the one we live on is the nicest — mmm … I don't know if I agree. It certainly is the only in habitable one, where we can have evolved life as we know it, especially humans — even if it's quite hot here, and some might deem that inhabitable! But it's not as hot as Venus, where you have metamorphic conditions at the surface. I think all these whirling fans in the lecture theatre wouldn't help us there, at a surface temperature on Venus of >450 °C — on average!

Nigel's main topic was isostasy, to explain why the Himalayas are as high as they are, and why mountains [in general] get to a certain height. He then went out to Venus and looked at the rocks that we have on Venus. Nigel gave an insight into how mountains grow on Venus — and, interestingly, why they are about the same height as Earth mountains. His conclusion was that basically the body size, the gravity and the rock strength are the three factors that control mountain range height.

He also looked at the very weird body that's not a planet, but a Moon. Nick explained that many years ago John Zarnecki's question *[see page 37— Editor]* first sparked off his interest in that body: Titan. Nigel explained that Titan has a water layer just under the crust — thus, things are a bit different and as a consequence, mountains are not as high om Titan as they are on Earth.

Finally, Sunday. On Sunday morning I think you share my thought that we all weren't quite as awake as we would have liked after a night of dancing and wine. Right? So, Dr Giulia Degli Alessandrini did an excellent job to keep us awake. She started by telling us that cats have rheology. And that makes for quite a cute picture about cats, right? That always wakes you up.

But Giulia also had a whole menu of world foods that she used as analogies for her studies; or better to say, to explain to us what all these very complex equations [about how rocks flow] are about. She only showed us two of those equations, and I think that was pretty much enough, with the wine we had last night. In summary, Giulia went from iced biscuits to crème brûlée, and ketchup. And it's actually a nice idea to understand why that ketchup wouldn't come out of the bottle. But, back to her science. She studies minerals in metamorphic environments. She took us to the Alps, and to the rocks that have mylonitic shear zones. Those allow us to understand how these mountain ranges formed and why they are where they are.

Next, we left the continents and went to the oceans. After all, the ocean is in our Symposium title, too. Dr Katrina Nilsson-Kerr talked about ancient rain and the oceans that are affected by monsoons. We learned that it is possible to trace back how much it rained in the past using ice and sediment cores. With this we

came back to research on these cores — the topic we started with Marcus Badger's evening lecture on Friday.

Katrina's talk taught us that 'the Monsoon' [the Indian Summer Monsoon] is very, very important for the ecosystems and the societies in the region, and that climate change can actually change the patterns of that monsoon. Such changes will not only impact vastly populated areas, where the monsoon itself occurs, but it also is a driver for the world's atmospheric circulation, the climate and the ocean circulation all around the world. Katrina conducts her research by using the tiniest — uh, not microns but µm, animals — foraminifera, the name of which I do not dare to actually try to pronounce! *[Globigerinoides ruber sensu-stricto — Editor]*

But what these tiny animals do is to build a calcite shell and thus preserve an isotopic record. Here we are again: isotopes! It is that isotope record that enables researchers like Katrina to trace back what actually happened in the time recorded in the ice core.

Right! Then we emerged from the ocean and looked at plants. Dr Julia Cooke, talked to us about silicon in plants, how it gets from the rocks into the plants, and how plants 'use it' for their defence, giving grazing animals 'paper cuts' with their sharp leaf edges. Especially, I think that paper cut example is something we all could relate to! Julia also explained how the extra silica wears down teeth of plant-eating animals, especially the small ones, and that plants react to being eaten by putting more silica into their leaves.

Then we had Professor David Rothery. He always rocks the audience. Today he spoke about Mercury, and told us how big the core of Mercury is compared to Earth's core. Although Mercury is very small, it's got a big core. Dave then gave an account which exciting missions we have had and are going to get around Mercury. And in the displays at the side of the auditorium there are maps of Mercury made in earlier research, proof of how we got to be able to map Mercury in that detail. Dave spoke about the BepiColombo Mission in detail, explaining how we will be able to explore all those details even further in the future.

"Professor David Rothery. He always rocks the audience."

But also there are many small, yet fascinating things. When Dave spoke about the instruments and how X-Ray Fluorescence works, I looked at his graph and I thought, "That's actually playing with electrons at another planet." And why I say this in that way is because when you go to another planet you always have to adapt your instruments — nothing works exactly as it does here on Earth. When I think about Mars, and think about the Martian instruments, they always bring data back that have this one little additional thing. Usually it's galactic cosmic rays and/or solar irradiation, something like that, which produces additional isotopes that we have to deal with when looking at the data. Mercury is blasted by irradiation, so good luck, Dave, with doing all your data de-convolution.

Dave also spoke about Mercury's lava flows and explosive volcanism. What surprised me when I heard this for the first time is that there is so much sulphur on Mercury, and it forms explosive volcanism. I was utterly surprised, and I thought that this can't really be, so close to the Sun, can it? Well, apparently it can. On Mercury there are holes that are produced by erosion; and many other crustal features — and I am looking forward to learn more with the arrival of the next spacecraft.

Last but not least in the line-up of speakers was Dr Mario Toubes-Rodrigo, who talked about the science in science fiction. I think he has almost convinced me that we can't find green men and bones on Mars, but only almost.

Mario talked about how we thrive on things that are not in equilibrium, and we — that's all life, from the bacteria to us — we use non-equilibrium to gain energy, and to digest what we eat. When he spoke about bio-signatures, he spoke a lot about methane — and I'm glad he mentioned Curiosity — or he wouldn't have gotten a favourable President's speech at the end! Mario gave details how Curiosity did find methane and Nomad did not; and how it could be seasonal or related to the dust storm we just had on Mars.

So are Martians nasty or are they friendly? Well, the science fiction literature is divided on that topic. And since Curiosity hasn't encountered any — Mario tells me we won't — but if we do I at least hope they don't carry a screwdriver. We will see. But the main point here is: if researchers are looking for life [on Mars], they are looking for bacteria. We haven't found any to date, but we have clues how we could look for them.

And there was a good point made in the questions, by commenting that we are looking for the life as we know it on Earth — but life elsewhere might be different. Mario responded that we need to start somewhere, with some basic assumptions to start looking for extraterrestrial life. And I bet even if life on Mars does not function in any way, shape or form like life on Earth, it will still cause that anomaly, that disequilibrium that will alert us to the fact that something is happening there that's not just geology.

I finish my summary about our line-up of speakers with saying, "Any field assistants who would like to do the running back and forth to the car for Mario next time he goes out in –5˚C?" [No volunteers were visible…] I don't think you have one! You need to do more, um, convincing.

To conclude, I'd like to say that at this OUGS Symposium we also had a Saturday afternoon that was a bit different. It was a bit different because Milton Keynes sits on a lot of clay, and the nearest geology, with few exceptions, is a long way away.

And so we decided we use what the OU is all about and put on some workshops, which could give you the opportunity to see how things are done, improve what you are already doing — and I know that there are excellent presenters out there; there are excellent writers out there; there are excellent photographers out there; and in the writing workshops David [Jones], Isabel [O'Brien] and I ran — we found that we learned as much from you as we could teach you, because there are excellent writers in this room, and we had a wonderful discussion — and that's what these workshops were about.

I've heard the same from Julia Cooke; I've heard the same from all the other workshop presenters and about the meadows walk, not to forget, and of course the lab tours.

The Saturday workshops and other activities included: 'Thin section microscopy' organised and run by Alan Richardson; 'Writing workshops' run by Dr Susanne Schwenzer, Dr David Jones and Isabel O'Brien; 'Presenting skills: getting attention, keeping it and leaving an impression' run by Dr Julia Cooke; 'Introducing photography: using your camera and taking photos in the field' run by Stacey Philips; OU 'Lab tours at selected instrumentation of the STEM Faculty, including electron beam and spaceflight instruments' by Dr Tom Barrett, Dr Giulia Degli Alessandrini, Dr Andrew Morse and Dr Simona Nicoara; and 'the 'Floodplain and natured walks on the OU Campus' run by Professor David Gowing.

And with that I concluded my President's speech and I hand over to [OUGS Chairman] Sue Vernon. [Applause]

Round the 'hairpin': an introduction to the geology of Syros (Cyclades, Greece) and guide to selected field locations

Duncan Woodcock

1 Introduction

The island of Syros (Fig. 1) is one of the best locations in Europe for the study of blueschist facies metamorphism. The north of the island, in particular, contains a large area of blueschist and eclogite facies rocks — developed by high-pressure, low-temperature (HP-LT) metamorphism of oceanic crust — that show minimal retrograde alteration. These unusual rocks are well exposed along the coast and at accessible inland locations. The area is the type location for the mineral glaucophane, a sodic amphibole (Fig. 2), which was first described in 1845 by the German petrologist Johann Hausmann, following his visit to Syros (Okrusch and Brocker 1990).

Systematic study of the geology of Syros began in the 1960s with Dixon's fieldwork for his PhD (Dixon and Ridley 1987), and since then the island has been intensively studied. However, despite good exposures, several important questions remain unanswered. Thus Syros remains a location for active research into the processes of burial and exhumation associated with blueschists and eclogites.

This article is the result of a two-week visit to Syros in April 2018, together with a review of some of the relevant recent literature. After an introduction to the regional geology of the Aegean, I review the stratigraphy, metamorphism and structural geology of the Cycladic Blueschist Unit (CBU) that makes up most of Syros. Finally, I present guides to selected field locations based on my own observations.

2 Regional geology of the Aegean

Convergence of Africa and Eurasia since the late Mesozoic has resulted in the development of a stack of crustal nappes that were detached from the lithospheric mantle of oceanic and continental microplates by subduction (Laurent *et al.* 2016). Reconstruction of the extent of the original crust from the stack of nappes indicates that some 2500km of lithosphere has been subducted since the Late Jurassic, and that this accords with the length of the subducted slab imaged by seismic tomography (Van Hinsbergen *et al.* 2005). The stack of nappes includes the CBU, which crops out extensively in the group of islands in the Aegean known as the Cyclades, together with Evvia and Attica in mainland Greece (Philippon *et al.* 2011).

When a subducting slab is dense it can sink more rapidly than the rate of plate convergence, thus the hinge zone and trench can 'roll back' oceanwards. Slab rollback to the south since the Oligocene has generated back-arc extension in the overriding plate. The resulting crustal extension has been focussed on large detachment faults that have contributed to the exhumation of the HP-LT rocks on Syros, the development of metamorphic core complexes and the opening of the Aegean Sea. In addition, slab rollback has moved the location of arc volcanism southwards to its current location in the south Aegean, centred on Santorini (Ring *et al.* 2010).

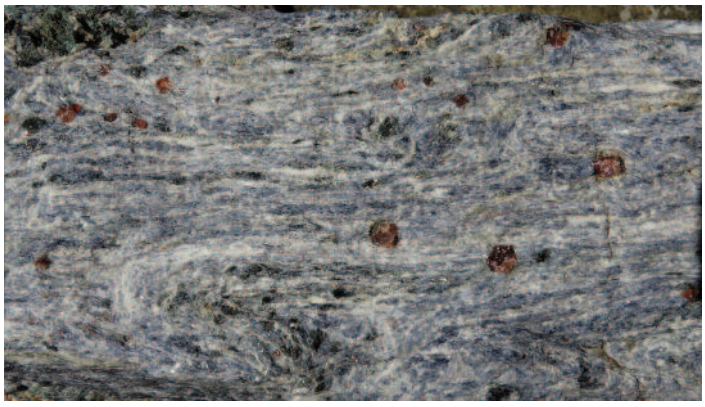
*Figure 2 This blueschist from west of Kini (*see *Fig. 22 for location) contains an abundance of the mineral glaucophane, which imparts the bluish-purple colour to the rock (garnets are* c. *3mm across).*

*Figure 1 An overview map of Syros, showing key locations mentioned in the text and the areas covered by the field guide maps. The areas marked 'mb' are outcrops of the metabasites and serpentinites of the Kambos Subunit (*see *Figure 3). The inset map shows the location of Syros.*

3 The geology of Syros

3.1 The CBU protolith

Much of the outcrop on Syros comprises various units of the CBU, which resulted from the burial and exhumation of the former Pindos Ocean. This ocean comprised a continental margin of Carboniferous basement overlain by a Mesozoic passive margin cover sequence of siliciclastics, carbonates and minor volcanics, together with a more distal deep marine sequence comprising mafic ocean crust and deep-sea sediments (Ring *et al.* 2010).



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3.2 Metamorphism

Burial of the CBU protolith in an accretionary wedge as a pile of nappes, and subsequent exhumation resulted in the 'tectonic stratigraphy' of Syros shown diagrammatically in Figure 3. The lithologies are the result of two episodes of metamorphism: a high-pressure low-temperature (HP-LT) metamorphism resulting from burial and a medium-pressure (MP) 'greenschist facies' overprint resulting from exhumation.

The HP-LT episode affected the whole of the CBU. Peak metamorphic conditions of 450–500°C and 15kbar were attained at *c.* 40–45Ma (Fig. 4, *opposite*). Evidence of even more extreme conditions, 550–580°C and 19–24kbar, has been obtained from some eclogite samples (Philippon *et al.* 2013). Preservation of the HP-LT blueschist and eclogite facies assemblages in northern Syros required that they were exhumed rapidly after burial. Early, synorogenic, exhumation is considered to have occurred in an 'extrusion wedge' above the subducting slab (Ring and Glodny 2010). Later, post-orogenic exhumation appears to be the result of back-arc extension in response to slab rollback.

The later greenschist facies metamorphism shows variable degrees of development on Syros, from minimal in the north to a pervasive retrograde alteration in the south of the island. This difference may reflect different exhumation histories for different rock units (Trotet *et al.* 2001). Greenschist retrograde alteration appears to be particularly well developed around the major shear zones, where the availability of fluids may have promoted retrograde reactions (Ring *et al.* 2010).

3.3 The Kambos Subunit

The Kambos Subunit comprises a metamorphosed 'tectonic melange' (Philippon *et al.* 2011) that contains blocks of metamorphosed fragments of mafic ocean crust embedded within a schistose matrix. These blocks comprise a range of lithologies, including eclogites together with jadeite-bearing rocks (Fig. 5, *opposite*), which are thought to be metamorphosed plagiogranites (Marschall and Schumacher 2012). The blocks tend to weather proud of the less resistant schistose matrix and are thus conspicuous features of the landscape (Fig. 6, *opposite*). They range in size from 1–10m, with most being <5m, although one large block, known as 'Monolith 1' comprises a block of glaucophane-eclogite some 20m high (Dixon and Ridley 1987). The prominence of these blocks, together with a mineral assemblage that is sensitive to changes in pressure and temperature, makes them relatively well studied features. In contrast, the schistose matrix, which is mapped as 'serpentinite' in some publications, is much less prominent and has a mineral assemblage that is stable over a wide range of pressures and temperatures; consequently it has attracted much less attention (Marschall and Schumacher 2012).

In detail, many of the blocks can be seen to have spectacular purple and green rinds (Fig. 7, *opposite*) surrounding an eclogite core. These metasomatic rims, known as 'blackwalls' (Marschall and Schumacher 2012), attest to the reaction of the block with the matrix material during prograde metamorphism, when the fluids released promoted diffusion along grain boundaries and thus mass transfer on a decimetre scale. As well as providing near-monomineralic samples of unusual minerals, the blackwalls provide evidence for mixing of mafic ocean crust with the matrix protolith in a 'tectonic melange' that was subsequently metamorphosed (Philippon *et al.* 2013).

3.4 Structural geology

Burial and subsequent exhumation of the CBU on Syros has resulted in multiple phases of deformation. An early prograde deformation (D_1) is locally preserved in the far north of the island, but is overprinted by a later (D_2) phase that is responsible for the prominent foliation, together with tight folds (Fig. 8, *opposite*), observed in the schists. A later D_3 phase can be observed in some locations, where a crenulation cleavage (Fig. 9, *opposite*) has folded and/or bent the dominant D_2 cleavage (Keiter *et al.* 2004).

The timing of D_2 relative to peak metamorphism can be established by study of foliated blueschists containing lawsonite pseudomorphs (Fig. 10),

Figure 3 'Tectonic stratigraphy' of Syros: The names of units, subunits and bounding faults are from Laurent et al. *(2016). The location of the Vari unit in the stratigraphy is controversial. The Chroussa Subunit comprises an alternating sequence of marbles and schists; the consensus appears to be that this was originally a single layer that is repeated by thrusting (Dixon and Ridley 1987).*

Vari Unit
gneisses
no HP metamorphism (controversial)
exposed in SE Syros

Vari Detachment

Cycladic Blueschist Unit

Kambos Subunit
metabasites, serpentinites, chlorite schist
- protolith: Pindos Ocean crust (mafic and sediments)
- blueschist and eclogite facies metamorphism
- generally unaltered during exhumation
- exposed in N Syros and other isolated locations

Kastri Shear Zone

Chroussa Subunit
alternation of marbles and schists, minor metabasites
- protolith: continental margin sediments
- blueschist and eclogite facies metamorphism
- variably altered to greenschist facies
- comprises much of the 'backbone' of Syros

Achladi-Delfini Shear Zone

Posidonia Subunit
intercalated gneiss and greenschists
- protolith: continental margin basement
- blueschist and eclogite facies metamorphism
- pervasively altered to greenschist facies
- exposed in SW Syros

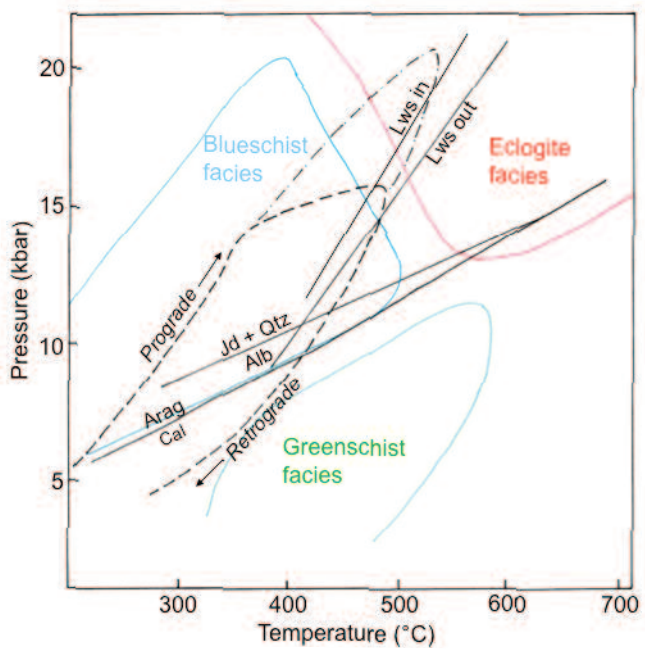

Figure 4 Pressure-temperature diagram for the metamorphic facies present in the Cycladic Blueschist Unit on Syros (based on Philpotts and Ague 2009). The P-T paths for marble-schist units (dashed) and for eclogite blocks in the tectonic melange (dash-dotted) are from Schumacher et al. *(2008). Cooling during decompression in northern Syros produced the 'hairpin' shape of the P-T paths. The conditions for lawsonite (Lws) decomposition are composition-dependent, indicated diagrammatically by the pair of sub-parallel lines: Jd = jadeite, Qtz = quartz, Alb = albite, Arag = aragonite, Cal = calcite.*

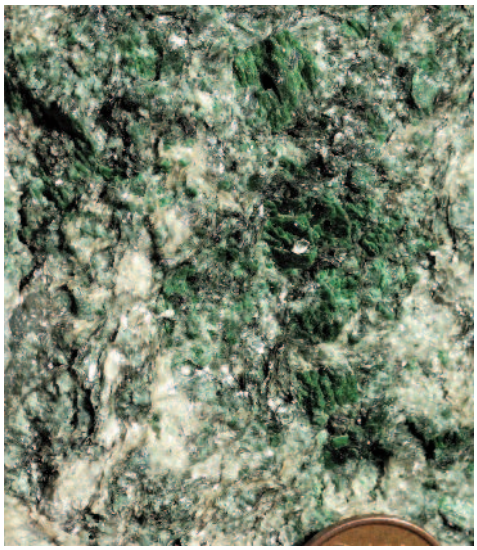

*Figure 5 The green sodic pyroxene jadeite shown here formed by the breakdown of albite at high pressure under blueschist facies conditions (*see *Fig. 4) (foreshore, west of Kini; see Fig. 22 for location).*

Figure 6 (below left) View to Lia Beach from c. *400m west of Kambos village. The prominent dark grey rock is 'Monolith 1' (*see *Fig. 19 for location).*

*Figure 7 (below right) A purple, glaucophane-rich rind on a small block within the Kambos Subunit (*see *Fig. 19 for location).*

Figure 8 (bottom left) Tight intrafolial folds in blueschist c. 400m west of Kambos village (see Fig. 19 for location; hammer handle 40mm wide).

Figure 9 (bottom right) Crenulation cleavage developed by D_3 deformation of the dominant D_2 foliation in a glaucophane schist. The crenulation plunges at 10° to 117° (magnetic) (location north-east of Kambos village at 37° 30' 18" N, 24° 53' 52" E; field of view c. *80mm × 50mm).*

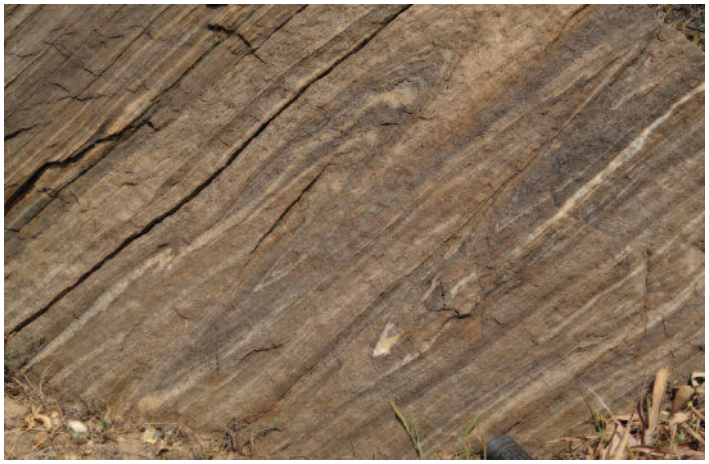

Figure 10 Lawsonite pseudomorphs c. *5mm in size in glaucophane schist. View at right angles to the foliation. Foreshore, south end of Lia Beach (*see *Fig. 19 for location).*

where the texture suggests that the original lawsonite porphyroblasts developed at about the same time as D_2. The lawsonite pseudomorphs comprise aggregates dominated by epidote and paragonite that are much more ductile than the original porphyroblasts and would not have survived the D_2 deformation. The breakdown of lawsonite in the presence of glaucophane is a prograde reaction that was largely complete before peak metamorphism was attained. Thus the blocky habit of the lawsonite pseudomorphs (Fig. 11) indicates that deformation was largely complete before peak metamorphic conditions were reached (Philippon *et al.* 2013).

Deformation during post-orogenic exhumation appears to have been restricted to large shear zones known as detachment faults that separate blocks of crust that remain largely undeformed.

Figure 12 Columnar aragonite pseudomorphs in marble (field of view c. *50mm × 55mm).*

Figure 11 Lawsonite pseudomorphs on a weathered surface parallel to the foliation in glaucophane schist, showing clearly the blocky habit of the original lawsonite porphyroblasts (location as Fig. 10; coin diam. 20mm).

This has enabled the preservation of the lawsonite pseudomorphs described above as well as columnar aragonite pseudomorphs within some of the marble units (Fig. 12). These distinctive columnar pseudomorphs were produced when aragonite (the high- pressure polymorph of calcium carbonate) inverted to calcite during exhumation (*see* Fig. 4). A pervasive deformation during this stage of exhumation would have destroyed both lawsonite and aragonite pseudomorph textures. Locally, within areas of high strain, lawsonite pseudomorphs are destroyed (Fig. 13)

Figure 13 The RHS of this image shows relatively undeformed blocky lawsonite pseudomorphs c. *5mm in size in blueschist. In contrast, the LHS is almost devoid of lawsonite pseudomorphs, which have been deformed beyond recognition within a shear zone (foreshore at Finikas).*

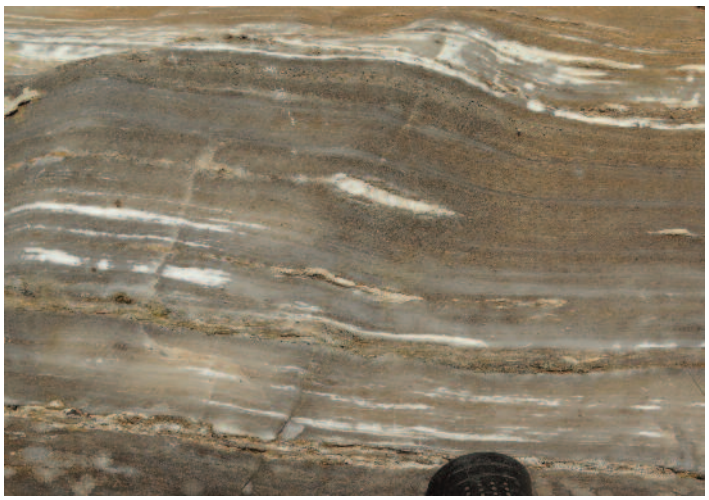

Figure 14 Mylonitic marble locally developed within a high strain zone (location 500m north-west of Kambos, 37° 29' 49" N, 24° 54' 45" E; hammer handle 40mm wide).

and the marbles are recrystallised with the development of mylonitic textures (Fig. 14).

Some of the most prominent structural features on Syros are late-stage brittle normal faults. The relative positions of schist and marble layers on either side of a fault are often picked out clearly by changes in vegetation (Fig. 15). The location of such faults is often obvious on the ground: marble units are relatively clear of vegetation and are thus easier to walk on when crossing open country; one sometimes finds them truncated by thick scrub, indicating the presence of schist on the other side of a fault.

The larger-scale structural geology is often complemented by the range of shear sense indicators that can be observed. Thus the metabasite Kambos Subunit contains structures that indicate a top-to-south movement, consistent with the emplacement of the unit on top of the schist-marble Chroussa Subunit (Philippon *et al.* 2011). Ductile shear zones associated with post-orogenic exhumation contain structures that indicate a top-to-east movement; this is particularly well illustrated in the Delfini area (Figs 16 to 18).

Figure 16 Stretched quartz porphyroclasts define a lineation within the foliation of a greenschist in the Delfini Shear Zone exposed on the peninsula to the north-west of Delfini (view is towards the north; see *Fig. 23 for location). The lineation plunges at 2° to 290°; it defines the approximately east–west 'transport axis' within the shear zone, but a suitable view at right angles to the lineation is needed to determine the sense of shear (*see *Fig. 17).*

Figure 17 A quartz porphyroclast c. *50mm across. The asymmetry of the porphyroclast indicates dextral (top to east) shear (view is towards 020°; location as Fig. 16).*

(see also Fig. 18, overleaf)

Figure 15 A pair of normal faults in a sequence of schists (vegetated) and marbles (unvegetated) (view is due north from 300m west of col between Varvarousa and Aetos beaches at 37° 28' 16" N, 24° 53' 54" E).

Figure 18 Isoclinal, intrafolial folds in greenschist on the foreshore, south side of the peninsula to the north-west of Delfini. This fold is one of a large number within a zone of intense deformation c. *100m wide on the peninsula, with dextral (top to east) shear. The fold axes plunge at 20° to 100° and define the transport axis (view is towards 350°;* see *Fig. 24 for location).*

4 Excursion guides

The following geological excursion guides are based on my own observations. Each comprises an annotated map that is intended to be largely self-explanatory.

(1) Kambos-Lia Beach (Fig. 19)
This excursion, which showcases aspects of the Kambos Subunit in the north of the island, would occupy a full field day.

(2) Grammata Bay (Fig. 20)
A full day excursion, accessed by a track from Kambos village that passes an abandoned marble quarry (Fig. 21, *opposite*). This excursion covers additional aspects of the metabasite unit, in particular the tectonic melange between the metabasite and the marble that is shown in Philippon *et al.* (2013, fig. 3).

(3) West of Kini (Fig. 22, *opposite*)
A small area of metabasite is exposed along the coast and shows a great variety of lithologies, including eclogites (Fig. 23, *opposite*) both *in situ* and loose on the bouldery beach. This 'geologists' sweetshop' could easily occupy half a day. Beware of overloading your rucksack!

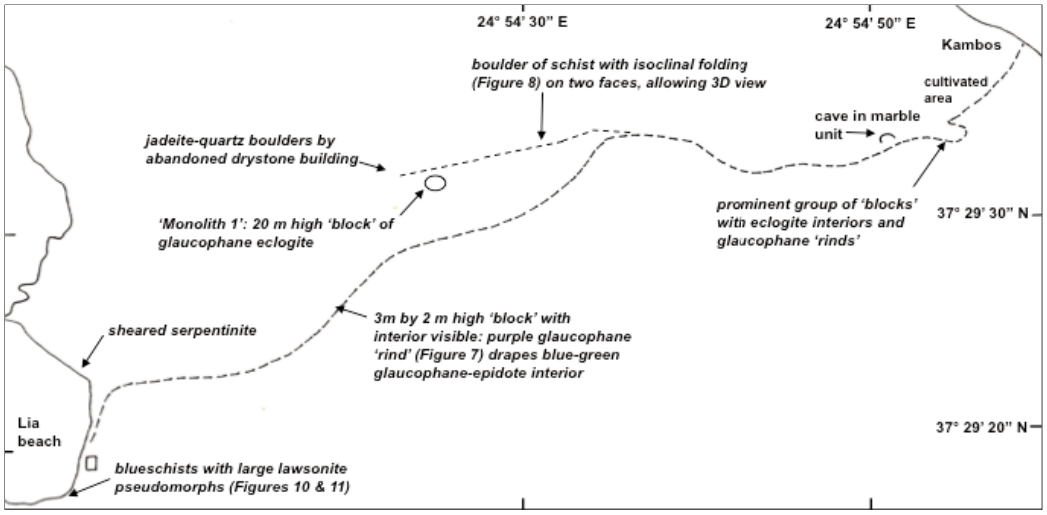
24° 54' 30" E
24° 54' 50" E
Kambos
boulder of schist with isoclinal folding (Figure 8) on two faces, allowing 3D view
cultivated area
cave in marble unit
jadeite-quartz boulders by abandoned drystone building
'Monolith 1': 20 m high 'block' of glaucophane eclogite
prominent group of 'blocks' with eclogite interiors and glaucophane 'rinds'
37° 29' 30" N
sheared serpentinite
3m by 2 m high 'block' with interior visible: purple glaucophane 'rind' (Figure 7) drapes blue-green glaucophane-epidote interior
Lia beach
37° 29' 20" N
blueschists with large lawsonite pseudomorphs (Figures 10 & 11)

Figure 19 (above) Kambos-Lia Beach excursion guide.

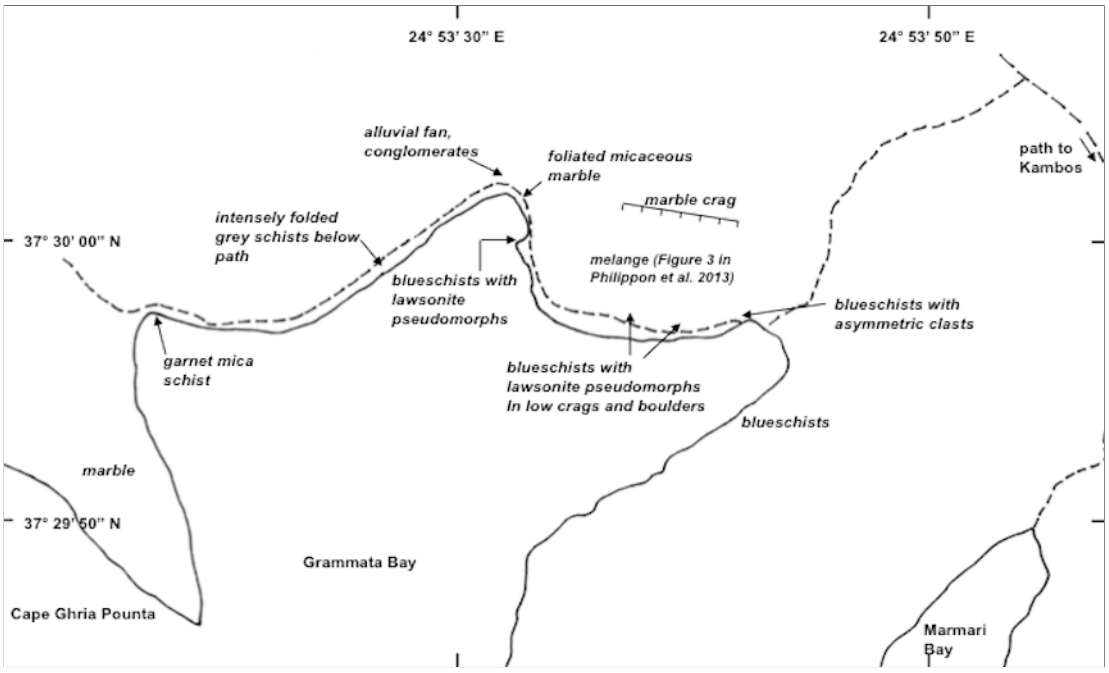

Figure 20 (below)Grammata Bay excursion guide.

Figure 21 An abandoned marble quarry with the west end of Grammata Bay in background (location north-east of Kambos village at 37° 29' 55" N, 24° 54' 26" E).

(4) Delfini (Fig. 24, *overleaf*)
This excursion includes the Delfini shear zone, which is beautifully exposed on the west side of the peninsula. A half day excursion, or longer if you wish to make detailed structural measurements.

(5) Fabrika-Katergaki (Fig. 25, *overleaf*)
This area was first mapped in detail by Julia Sable while a student at Amherst College, Massachusetts. My map does not do justice to her detailed work (Sable 2000) but provides an introduction to this coastal traverse through blueschist facies rocks, with some large garnets (Fig. 26, *page 75*), to the marble unit at Katergaki. I spent a whole day here and moved less than a kilometre!

Figure 22 (below) West of Kini excursion guide; right-hand map shows the location of the area studied.

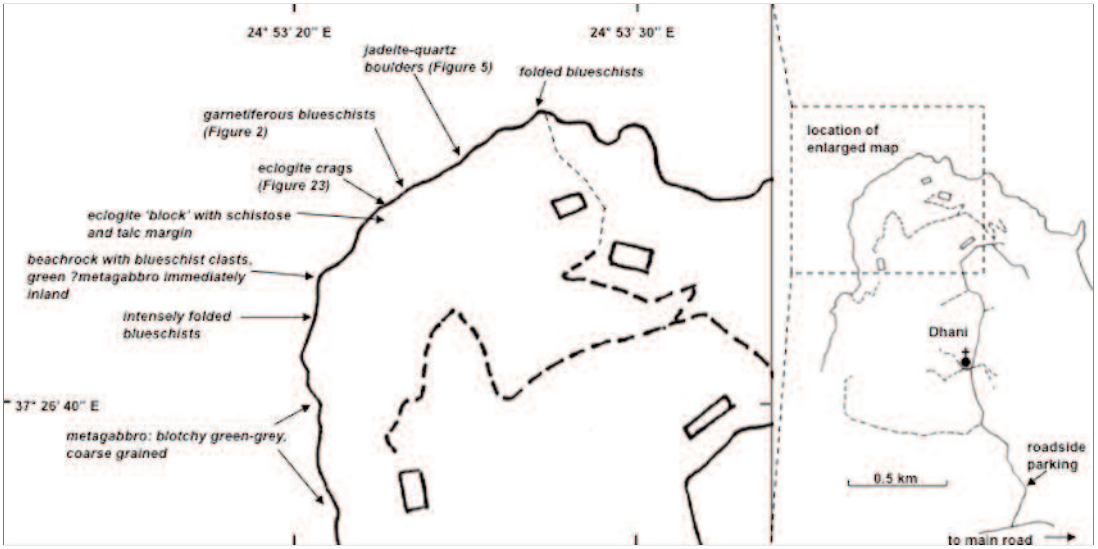

*Figure 23 Eclogite boulder on the foreshore, west of Kini. This coarse-grained rock is the result of high-pressure metamorphism of a mafic protolith, when plagioclase breaks down to be replaced by garnet. Sodium from the plagioclase is incorporated into the sodic pyroxene omphacite, which is the greenish mineral present (*see *Fig. 22 for location; field of view* c. *70mm × 50mm).*

The following localities were also visited and found to be geologically interesting:

(i) Finikas
A small coastal exposure comprises lawsonite blueschists that have locally been cut by shear zones, within which the lawsonite pseudomorphs have been deformed beyond recognition (*see* Fig. 13). Away from the shear zones, the blocky habit of the original lawsonite is well displayed. Philippon *et al.* (2013, fig. 4) provides a detailed map of the exposure, which is best examined in early evening sunlight.

(ii) Komito area
The pervasive greenschist facies overprint that characterises much of the south of Syros can be examined at Komito Beach. A trail running SSW from the beach allows access to the southern tip of Syros and runs through schists and gneisses on the Posidonia basement unit.

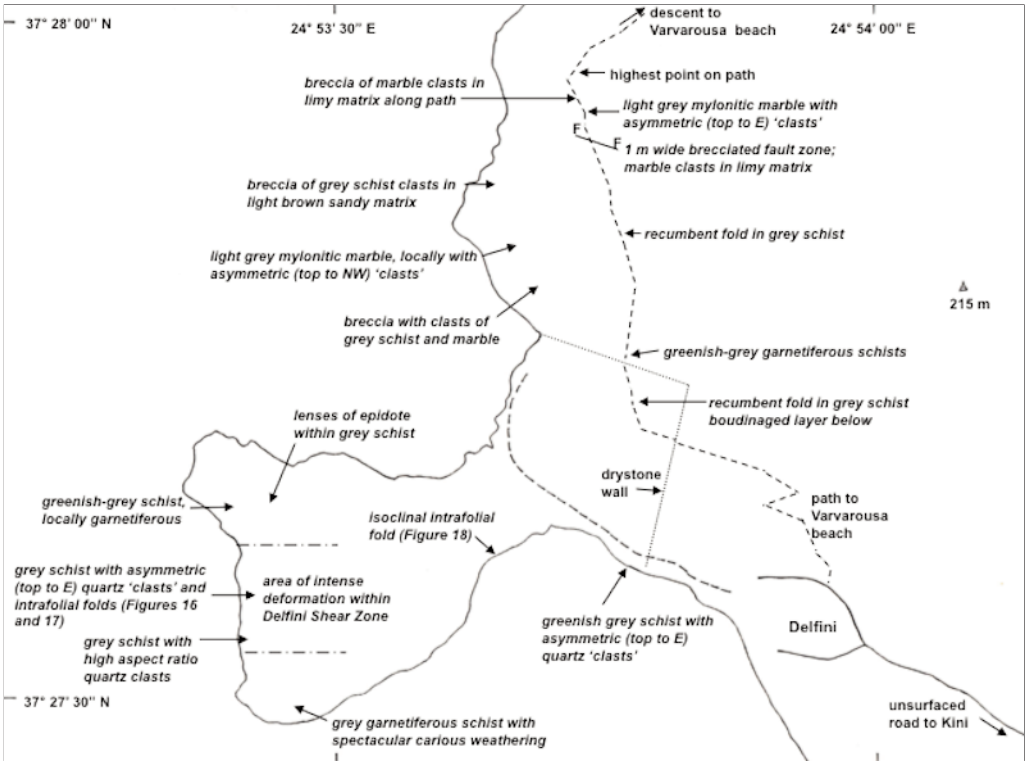
37° 28' 00" N
24° 53' 30" E
descent to Varvarousa beach
24° 54' 00" E
highest point on path
breccia of marble clasts in limy matrix along path
light grey mylonitic marble with asymmetric (top to E) 'clasts'
1 m wide brecciated fault zone; marble clasts in limy matrix
breccia of grey schist clasts in light brown sandy matrix
recumbent fold in grey schist
light grey mylonitic marble, locally with asymmetric (top to NW) 'clasts'
215 m
breccia with clasts of grey schist and marble
greenish-grey garnetiferous schists
recumbent fold in grey schist boudinaged layer below
lenses of epidote within grey schist
drystone wall
path to Varvarousa beach
greenish-grey schist, locally garnetiferous
isoclinal intrafolial fold (Figure 18)
grey schist with asymmetric (top to E) quartz 'clasts' and intrafolial folds (Figures 16 and 17)
area of intense deformation within Delfini Shear Zone
greenish grey schist with asymmetric (top to E) quartz 'clasts'
Delfini
grey schist with high aspect ratio quartz clasts
37° 27' 30" N
unsurfaced road to Kini
grey garnetiferous schist with spectacular carious weathering

Figure 24 (above) Delfini excursion guide.

Figure 25 (below) Fabrika-Katergaki excursion guide.

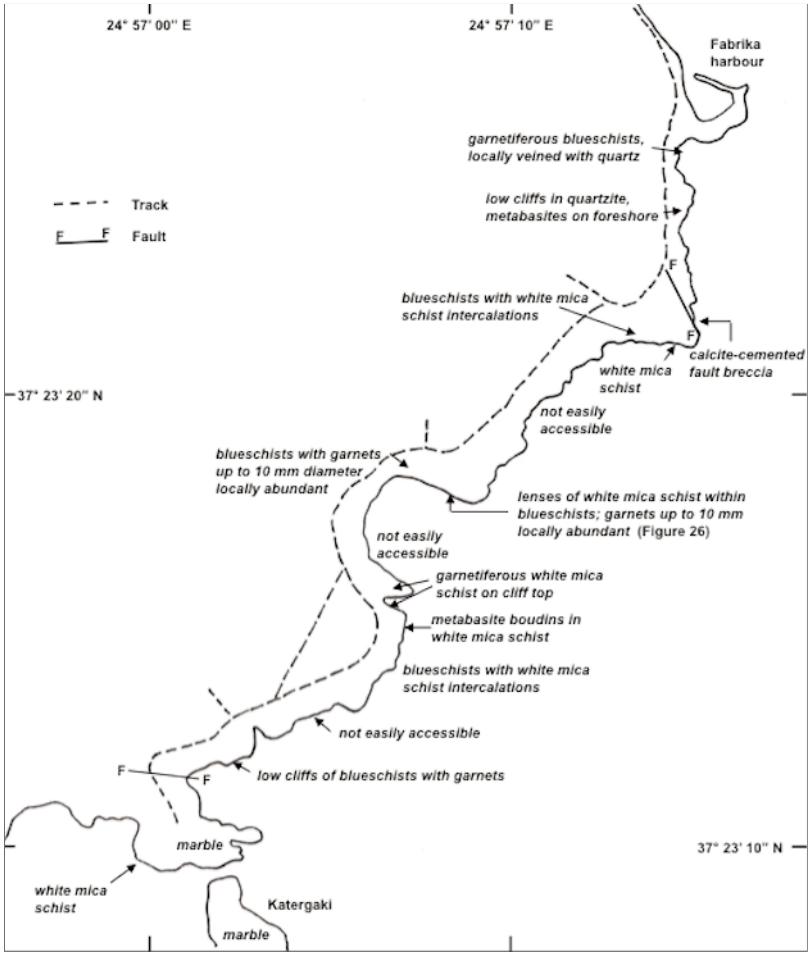
24° 57' 00" E
24° 57' 10" E
Fabrika harbour
garnetiferous blueschists, locally veined with quartz
Track
Fault
low cliffs in quartzite, metabasites on foreshore
blueschists with white mica schist intercalations
calcite-cemented fault breccia
white mica schist
37° 23' 20" N
not easily accessible
blueschists with garnets up to 10 mm diameter locally abundant
lenses of white mica schist within blueschists; garnets up to 10 mm locally abundant (Figure 26)
not easily accessible
garnetiferous white mica schist on cliff top
metabasite boudins in white mica schist
blueschists with white mica schist intercalations
not easily accessible
low cliffs of blueschists with garnets
marble
37° 23' 10" N
white mica schist
Katergaki
marble

*Figure 26 Garnets in a 'whiteschist' comprising quartz and phengite mica. Although the rock was produced within the blueschist metamorphic facies, the protolith composition was unsuitable for the development of glaucophane. North of Katergaki (*see *Fig. 25 for location; coin diam. 20mm).*

Acknowledgements

I would like to thank Professor Jan Wijbrans and Bertram Uunk from VU University, Amsterdam (who, by chance, were staying at the same accommodation) for their help in improving my understanding of the geology of Syros.

References

Dixon, J., and Ridley, J. 1987 'Syros: chemical transport in metasomatic processes', *in* Helgeson, H. C. (ed) *Nato Advanced Study Institutes Series. Series C* Dordrecht: D. Reidel Publishing Company, 489–500

Keiter, M., Piepjohn, K., Ballhaus, C., Lagos, M., and Bode, M. 2004 'Structural development of high-pressure metamorphic rocks on Syros island (Cyclades, Greece)'. *J Structural Geol* **26**, 1433–45

Laurent, V., Jolivet, L., Roche, V., Augier, R., Scaillet, S., and Cardello, G. L. 2016 'Strain localization in a fosillized subduction channel: insights from the Cycladic Blueschist Unit (Syros, Greece)'. *Tectonophysic* **672–673**, 150–69

Marschall, H. R., and Schumacher, J. C. 2012 'Arc magmas sourced from melange diapirs in subduction zones'. *Nature Geosci* **5**, 862–7

Okrusch, M., and Brocker, M. 1990 'Eclogites associated with high-grade blueschists in the Cyclades archipelago, Greece: a review'. *Europ J Mineral* **2**, 451–78

Philpotts, A. R., and Ague, J. J. 2009 *Principles of Igneous and Metamorphic Petrology*. Cambridge UP

Philippon, M., Brum. J-P., and Gueydan, F. 2011 'Tectonics of the Syros blueschists (Cyclades, Greece): from subduction to Aegean extension'. *Tectonics* **30**, TC4001

Philippon, M., Gueydan, F., Pitra, P., and Brum, J-P. 2013 'Preservation of subduction-related prograde deformation in lawsonite pseudomorph-bearing rocks'. *J Metamorphic Geol* **31**, 571–83

Ring, U., and Glodny, J. 2010 'No need for lithospheric extension for exhuming (U)HP rocks by normal faulting'. *J Geol Soc, London* **167**, 225–8

Ring, U., Glodny, J., Will, T., and Thomson, S. 2010 'The Hellenic subduction system: high-pressure metamorphism, exhumation, normal faulting, and large-scale extension'. *Ann Rev Earth Planetary Sci* **38**, 45–76

Sable, J. E. 2000 'Structure and petrology of mafic and siliceous schists at Katergaki Point, Syros, Greece'. https://keckgeology.org/files/pdf/symvol/13th/Greece/sable.pdf (accessed 25 May 2018)

Schumacher, J. C., Brady, J. B., Cheney, J. T., and Tonnsen, R. R. 2008 'Glaucophane-bearing marbles on Syros, Greece'. J *Petrology* **49**, 1667–86

Trotet, F., Vidal, O., and Jolivet, L. 2001 'Exhumation of Syros and Sifnos metamorphic rocks (Cyclades, Greece): new constraints on the P-T paths'. *Europ J Mineral* **13**, 901–20

Van Hinsbergen, D. J. J., Hafkenscheid, E., Spakman, W., Meulenkamp, J. E., and Wortel, R. 2005 'Nappe stacking resulting from subduction of oceanic and continental lithosphere beneath Greece'. *Geology* **33**, 325–8

Appendix: a note on latitude, longitude and magnetic declination

Latitude and longitude were determined with a Garmin eTrex hand-held GPS unit, set to the WGS 84 map datum, with a minimum of six satellites in view. In all cases the error displayed was less than +/– 10m, corresponding to +/– 0.3'' of latitude. All orientations referred to in the text are magnetic bearings, determined with a Silva type 15T compass. The magnetic declination was 5° E in 2018.

Book review

Park, Graham 2020 *Breakthroughs in Geology: Ideas that Transformed Earth Science*. Edinburgh: Dunedin (ISBN 978-1-78046-076-5; xvii + 262pp; hardback £24.99; also as PDF 978-1-78046-624-8, ePub 978-1-78046-614-9 and Kindle 978-1-78046-615-6)

This volume is a welcome history of major geological 'success stories', based on the solid, steady fieldwork and research of dedicated scientists through more than a hundred years.

The book's dust jacket quotes James Hutton's "no vestige of a beginning — no prospect of an end." As geologists have come to realise, geological understanding comes both from slow, accumulative processes *and* from periodic and arbitrary catastrophic occurrences that drive the shaping of the Earth. Prof. Graham Park's text relates how geological research does not necessarily flow steadily onwards in small incremental advances, but both by accumulated, hard-won evidence punctuated by a series of significant discoveries — in facts and in realisations — and of interpretations.

Such a history necessarily involves choices. Park is honest is admitting that writing the book was "bound to be subjective and controversial." I disagree. In my opinion Prof. Park has grouped his history around what must be topics that would be agreed with by most geologists. His chapter titles reflect the major 'breakthroughs', and their content goes on to include a wealth of supporting 'evidence' — each packet of which itself contributes to that steady flow that has led to significant discoveries and interpretations.

The topic heads that indicate the subject matter comprise 12 chapters. By no means do the titles limit the information within them that led to the main theme. These are:

1 Uniformitarianism
2 Evolution and the *Origin of Species*
3 Continental drift
4 Mantle convection: a mechanism for continental drift?
5 Deformation ellipsoid to ductile shear zone
6 Plate tectonics
7 Ophiolites: clues to the ocean crust and mantle
8 Fault systems kinematics
9 Back-arc basins and trench roll-back
10 Hot-spots and mantle plumes
11 Sequence stratigraphy
12 Gravity spreading

Although not entirely historically chronological, as the story unfolds it is often the case that the research, interpretations and breakthroughs of the previous chapter flow into the next topic and contribute to its accumulations of evidence and discovery. Each of these themes comprises truly Earth-forming phenomena. The text is well written and there are plenty of photographs, diagrams and charts to illustrate the ideas described — 130 figures — but not to overwhelm it. The information in each chapter is frequently under subsections headed by the principal geologist(s) who made the discovery or developed the evidence and interpretations. There is also much interesting biographical information about the geologists doing the research and reaching the breakthroughs — sufficiently relevant but not too much information.

Most of the chapters end with a 'Postscript' that links the themes in the previous and following chapter(s), thus building the story. Geology students can, in fact, learn much geology from the book as well as how the field has developed, for in linking the themes Park's narrative presents a wholeness to the subject matter that is sometimes hard to grasp when studied as 'modules' on topics.

The book is not free of editorial 'problems'. I found a little confusing his sourcing of the figures and the citing of sources within the text, for they are separate lists: the former at the front of the book and the latter at the end (by chapter). While listing references by chapters is fine, the separation of the two lists has on occasion led to some being cited in the wrong list or occasionally missed out altogether. Thus a citation at the end of a caption, which appears in the same Harvard format as a text citation is not in the chapter references (unless also there as a source), but in the illustrations source list in the book's prelims.

As well as these two sources and references lists, there is a useful Glossary and a detailed Index. Refreshingly, the glossary includes all the major terminology used in the text without those terms being, to me, annoyingly emboldened within the text — this is not a textbook, it is a history of geology.

As an archaeologist, historian and keen student of the history of science, this book will take a prominent place among my stratified bookshelf foresets and bedforms. At £24.99 for the hardback it's worth every penny.

— Dr David M. Jones, OUGS Proceedings Editor

OUGS visit to Solnhofen, Bavaria

led by John Nudds and Cindy Howells, 13–19 May 2019

Averil Leaver (AL), Janet Hellen (JH), Maggie Deytrikh (MD), Linda Fowler (and Ed) (LF), Kath Addison-Scott (KAS), Norman Nimmo-Smith (NN-S), Joyce Ali (JA)

Introduction

Averil Leaver

At the Severnside AGM held in Cardiff in January 2018 we had a talk by Cindy Howells from the National Museum of Wales on '*Archaeopteryx* — the bird-like dinosaur'. I took some photographs of the casts that Cindy showed us of the London and Berlin specimens (Figs 0.1 and 0.2).

This talk inspired many of us and we asked Jan Ashton-Jones to organise a trip to Bavaria to visit Solnhofen, the home of this fossil, to enable us to see some of the original fossils that Cindy had talked about.

The trip took place in May 2019, led by Dr John Nudds of the University of Manchester, co-author of a paper on *Archaeopteryx* No. 8, the 'Daiting Specimen' (Kundrát *et al.* 2019). The main aim of the trip was to see as many of the 14 known *Archaeopteryx* fossils as possible (Table 1, *overleaf*).

As you can see some of the specimens are not kept in Germany, but we were able to visit three museums that housed *Archaeopteryx* fossils and casts. Unfortunately, the Jura Museum in Eichstätt was closed during our visit. All the museums we visited exhibited a wide variety of beautiful fossils and also showed the uses to which the lithographic limestone has been put.

We also spent time hunting for our own fossils in some of the quarries where *Archaeopteryx* and other important fossils had been found, with varying success. Most of us found coprolites and the delightful *Saccocoma*, and one of our members, Terry Blake, found a small lobster. Terry gave it to Dr Martin Röper as a donation to the Bürgermeister Müller Museum and it has been identified as *Eryon cuvieri*, the first specimen of this species to be recorded from the Mörnsheim Formation (Selden and Nudds 2012).

Figure 0.1 The London Specimen of Archaeopteryx lithographica *(AL).*

Figure 0.2 The Berlin Specimen of Archaeopteryx lithographica] *(AL).*

Setting the scene

Janet Hellen

Palaeogeography and climate

In the Jurassic Period (208–146Ma), the Bavarian region was just to the north of the Tethys Ocean as Laurasia rifted from Gondwana. The landmass to its north was being compressed by the Central Atlantic rifting process and to its south by the consequent movement of the African plate that eventually closed the Tethys Ocean by the end of the Cretaceous Period (Fig. 0.3, *overleaf*).

During the Lower Jurassic, the Eichstätt region was initially submerged in a marginal shelf sea on the shore of the Tethys Ocean, but by the Upper Jurassic, at 150Ma, the area was covered by a shallow inland sea. With a semi-arid and subtropical climate at 25˚–30˚N, and only intermittent monsoon-driven marine incursions, its normally low energy waters enabled reef mounds of sponges and blue-green algae to form. These developments created local basin enclaves, protected from Tethys waters to their south and east, in which cyclically deposited micritic lime mud deposits, known as *Plattenkalk*, accumulated in the Tithonian over a period of *c*. 4Ma (Fig. 0.4, *overleaf*).

Palaeoenvironment

As the central European region became uplifted tectonically at the end of the Jurassic, the inland sea became more a collection of lagoons between mounds, some of which formed isolated reefs and islands on which terrestrial organisms were able to thrive and evolve; this palaeogeography is reflected in the present-day outcrop pattern (Fig. 0.5, *page 79*).

In the warm climate, high evaporation rates caused stratification of the basin waters. The oxygenated surface waters supported plenty of fresh or brackish water nektonic life, but deeper, more saline, stagnant bottom waters were toxic to living organisms — benthic, scavenging and burrowing biota were absent and decay by bacterial action very limited. However, cyanobacteria that lived in the anoxic conditions may have contributed to the preservation and burial of organisms by binding the carbonate, encapsulating them and preserving their tracks on the lagoon floor. It has been proposed that violent monsoon storms affected the region, mixing the stratified water layers, and causing sudden saline upwellings that killed surface-water-dwelling organisms. The composition of the *Plattenkalk* was affected by marine water

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Table 1 *Archaeopteryx* fossils and their locations

Number	*Known as*	*Name*	*Location*	*Date found*
	The Feather	*Archaeopteryx lithographica*	Museum für Naturkunde, Berlin (main part) Bavarian State Museum for Geology and and Palaeontology, Munich (counterpart)	August 1861
No. 1	The London Specimen	*A. lithographica*	Natural History Museum, London	1861
No. 2	The Berlin Specimen	*A. lithographica*	Museum für Naturkunde, Berlin	1876
No. 3	The Maxberg Specimen	*A. lithographica*	Lost	1956
No. 4	The Haarlem Specimen	*Ostromia crassipes*	Teylers Museum, Haarlem, The Netherlands	1855 (but not described until 1970s)
No. 5	The Eichstätt Specimen	*A. lithographica*	Jura-Museum, Eichstätt, Germany	1951
No. 6	The Solnhofen Specimen	*A. lithographica*	Bürgermeister Müller Museum, Solnhofen, Germany	1988
No. 7	The Munich Specimen	*Archaeopteryx bavarica* or *A. lithographica* juvenile	Bavarian State Museum for Geology and Palaeontology, Munich	1992
No. 8	The Daiting Specimen or 'The Phantom'	*Archaeopteryx albersdoerferi*	Dinosaur Park, Altmühltal, Denkendorf, Germany	?1990
No. 9	The Chicken Wing	*A. lithographica*	Bürgermeister Müller Museum, Solnhofen, Germany	2004
No. 10	The Thermopolis Specimen	*A. lithographica*	Wyoming Dinosaur Center, Thermopolis, Wyoming, USA	2005
No. 11	The Altmühl Specimen	*A. lithographica*	Bürgermeister Müller Museum, Solnhofen, Germany	2011
No. 12	The Schamhaupten Specimen	*A. lithographica*	Dinosaur Park, Altmühltal, Denkendorf, Germany	2010
No. 13	The Mülheim Specimen	*Alcomonavis poeschli*	Bavarian State Museum for Geology and Palaeontology, Munich	2017

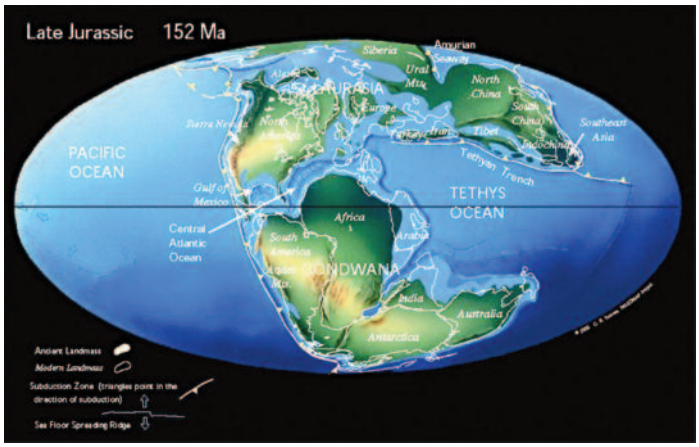


Figure 0.3 During the Upper Jurassic, Solnhofen lay in a shallow marine area on the northern side of the north-western end of the closing Tethys Ocean (Scotese 2002).

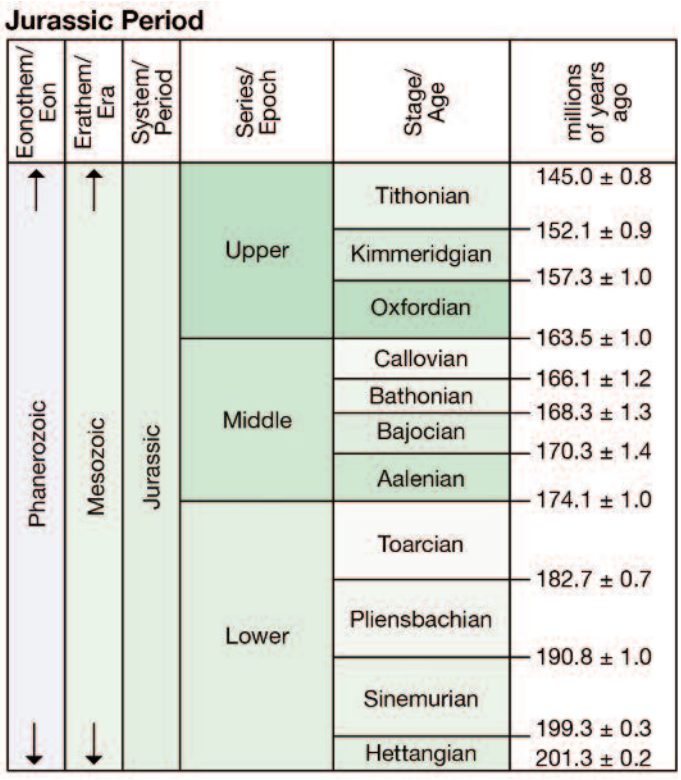


Figure 0.4 Subdivision of the Jurassic system according to the ICS, 2017 (Tang 2013).
(Published with permission from the International Commission on Stratigraphy (ICS). International chronostratigraphic units, ranks, names and formal status are approved by the ICS and ratified by the International Union of Geological Sciences (IUGS). Source: 2012 International Stratigraphic Chart produced by the ICS.)

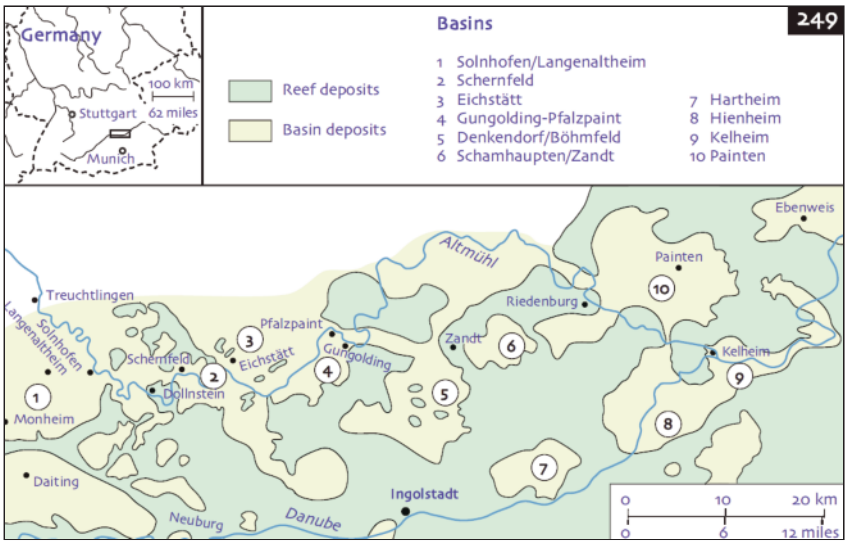


Figure 0.5 Locality map showing the Plattenkalk *basins in the Solnhofen Limestone region of the Southern Franconian Alb, Bavaria, in Southern Germany (after Barthel* et al. *1990, as in Selden and Nudds 2012).*

Figure 0.6 Typical quarry wall showing Flinz und Faüle *bedding in the Solnhofen* Plattenkalk *beds (Stiegler 2006).*

influxes that imported both open sea-dwelling and boundary-reef community organisms into the basins. These included air-borne vascular plant fragments, flying insects, ammonites, crustaceans, turtles, fish, *Archaeopteryx* and pterosaurs from the nearby continent margin, reef tops or ocean. These non-indigenous (allochthonous) organisms died, together with any 'drowned' local aquatic surface-dwelling biota, as soon as they reached the deeper anoxic basin waters.

Storm-disturbed waters stirred up fine carbonate ooze from around reef bases and deposited this as lamellae of fine-grained, nearly pure calcium carbonate (80%), known locally as '*Flinz*'. The *Flinz* rapidly buried any fresh corpses in the basins as it settled out of suspension and its paper-thin, finely interlocked microsparite layers preserved in fine detail the impression of the upper surface of fossilised remains. The typically deposited, lower percentage carbonate, less-pure, micrite (*Faüle*) forms the 'bed' or counter-slab layer on which remains lie today. *Faüle* contains a mix of carbonate mud, eroded fossil fragments and clay, and often carries preserved imprints of the under-surface relief of fossil remains and tracks. The *Flinz* and *Faüle* facies (Fig. 0.6) seem to be associated with cyclic conditions such as monsoons or carbonate-generating algal blooms and are a feature within the *c.* 95m thick Tithonian (152.1–145.6Ma) Solnhofen *Plattenkalk* beds, deposited from 150Ma over a limited period of 0.5–0.7Ma (Fig. 0.7).

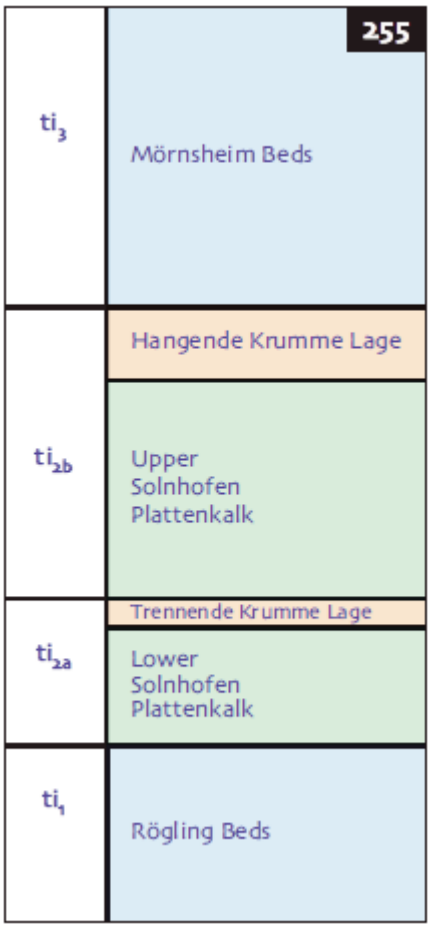


Figure 0.7 Diagram to show the Tithonian stratigraphy of the Upper Jurassic succession in the Solnhofen-Eichstatt (after Barthel et al. *1990, as in Selden and Nudds 2012).*

The Solnhofen *Plattenkalk* extends over 70km^2. Its Jurassic lagoon water depth varied locally and gently increased eastward beyond Mörnsheim, with deep-water fauna fossils predominant at the abandoned Zandt and Kelheim quarries (*see* Fig. 0.5, basins 6 and 9). The limestone has been exploited from at least Roman times for floor and wall tiles and, from the 17th century, for lithographic printing. Consequently, many different local quarry names were given to the limestone formations involved. The lithographic limestone beds vary from a siliceous carbonate in the east of the region to almost pure calcium carbonate at Eichstätt, which is older than the comparable beds at Solnhofen. These variations reflect different, but synchronous, deposition conditions occurring within different basins in the lagoon area. With fine-tuning using ammonite zone dating, a need for revision of the Solnhofen Formation lithostratigraphic names therefore arose (Fig. 0.8, *overleaf*).

The stratigraphic range of the discoveries of the Bavarian primitive fossil avian *Archaeopteryx* spanned *c.* 152–150Ma, from the Late Kimmeridgian boundary to the Mid-Tithonian. The Solnhofen and Eichstatt limestones are within the Altmühltal Formation. The range of fossil forms of *Archaeopteryx* with avian characteristics within such a tight time span is attributed to independent evolution on the scattered sites of the archipelago of islands that had developed in the lagoon area by this time (Fig. 0.9, *overleaf*).

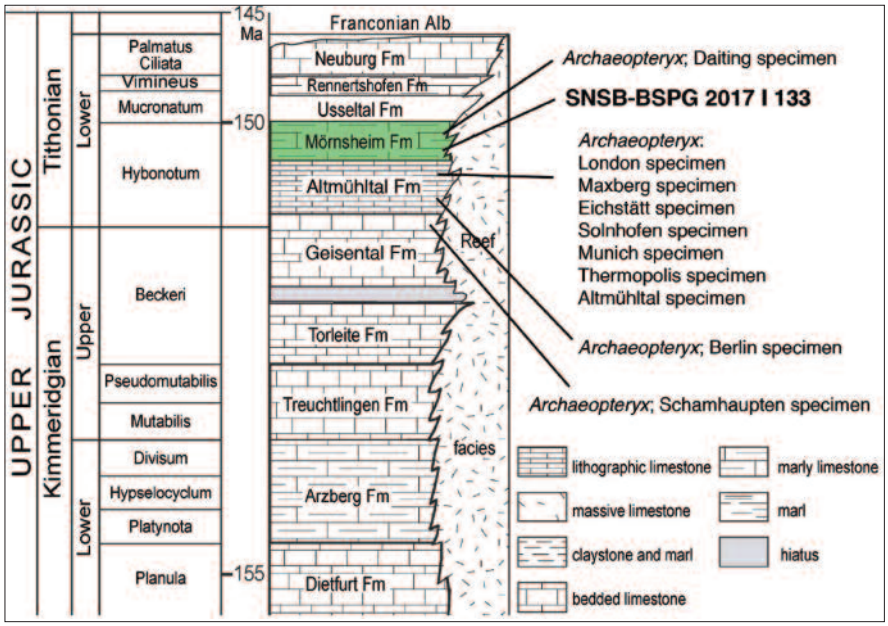


Figure 0.8 Revised lithostratigraphy of the 'Solnhofen Limestones' showing the levels at which various specimens have been found (Rauhut et al. *2019).*

A geological cross-section through the Solnhofen area, on display at the Bürgermeister Müller Museum, shows steadily south-dipping Upper Jurassic sedimentary facies, deeply incised by river valleys and showing limited exposures of Tithonian lithographic facies at Solnhofen and Mörnsheim (Fig. 0.10).

Quarrying by hand extraction of the relatively fragile limestone for luxury tiles continues today, with the consequent discovery of many intact, highly detailed fossils. These fossils often include soft tissue such as muscles, feathers and organs, and trace fossils such as coprolites. This led, from the 19th century, to international interest in their discovery and appreciation of their significance. During our trip we were able to visit some of these quarries, extract our own geological specimens and also see examples of the best and most significant examples that have been discovered.

Day 1, Tuesday 14 May 2019: Munich

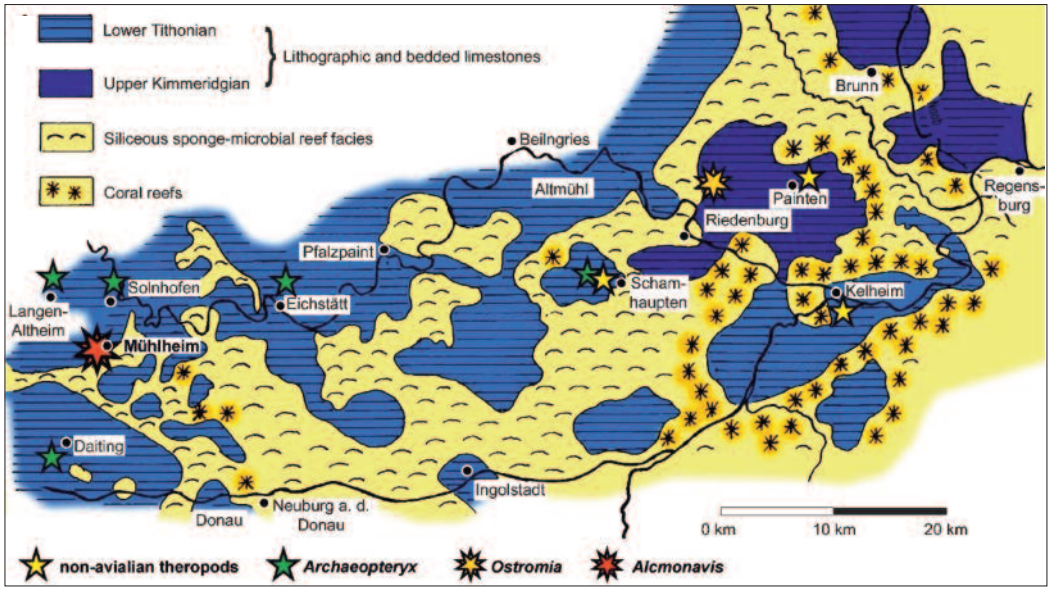
Maggie Deytrikh

Our trip provided a wonderful insight into the history and life of *Archaeopteryx* and the Solnhofen Limestone, as we were expertly guided around Munich and Bavaria by John Nudds and Cindy Howells. Our first day was spent in the city of Munich, and after a baptism of fire negotiating the Munich Metro ticket machines we found the Bayerische Staatssammlung für Paläontologie und Geologie (Bavarian State Collection of Palaeontology and Geology) in Richard Wagner Straße (Fig. 1.1, *opposite*).

Dr Oliver Rauhut, the Museum Curator (and university Lecturer, expert and author on *Archaeopteryx*), showed us the storage area, where several original specimens are kept. The skeletal fossils of *Archaeopteryx* are numbered according to when they were found, and many of them also have an informal name, such as the 'Munich Specimen'. Indeed, more recently, some have been classified as different species altogether, but the traditional nomenclature continues to be used to describe these fossils, all of which were thought originally to have been of *Archaeopteryx* and found in the Kimmeridgian–Tithonian (157–145Ma) limestones of Bavaria.

The depositional environment in which they lived was a quiet, restricted lagoon with hypersaline waters in a semi-arid climate. These early birds would have flown over these lagoons, succumbed and drowned during storms. Rapid burial in carbonate ooze has enabled exceptionally detailed preservation of these iconic fossils, which includes the soft tissues, feathers and even some stomach contents [preserved in the dinosaur *Compsognathus*, but not in *Archaeopteryx* —Ed.].

Figure 0.9 Map of the southern Franconian Alb with palaeogeographic settings indicated and showing the locations of major finds (Rauhut et al. *2019).*



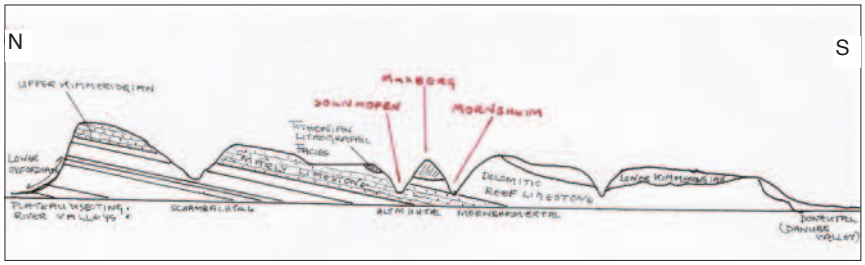


Figure 0.10 North–south cross-section through the western Plattenkalk of the Southern Franconian Alb, Bavaria (sketch by JH from display at Solnhofen Museum).

Figure 1.1 Bayrische Staatssammlung für Paläontologie und Geologie in the 150-year-old 'School of Applied Arts' building (MD).

There are many limestone quarries in the Solnhofen area. The fine-grained, hard, pure micritic limestone was extracted for building purposes and used as floor and roofing tiles, as it splits easily. It was also found to be ideal for printing, and called lithographic limestone; hence, the species name *Archaeopteryx lithographica*.

Archaeopteryx is arguably the most famous fossil of all, representing one of Charles Darwin's postulated 'missing links', or transitional forms, in this case between dinosaurs or reptiles and birds, which supported his theory of 'natural selection' (i.e. evolution) in *On the Origin of Species*, published in 1859. Only two years later, in 1861, an isolated fossil feather was found, followed later in the same year by the first skeletal fossil of *A. lithographica*. This chicken-sized animal soon became the centre of a heated evolutionary debate in the 19th century.

The four specimens that we saw in the storage area were: the counterpart of The Feather, the Munich Specimen, the theropod dinosaur *Compsognathus*, and the 13th specimen, now described as *Alcmonavis poeschli*.

The Feather

Hermann von Meyer found this 60mm long fossilised feather in the Solnhofen Community Quarry in 1861. Its significance lies in its asymmetry, which indicates some ability to fly. This represented the first evidence of any flying 'early bird', 'feathered dinosaur' or 'evolutionary transition' in the Mesozoic. We saw the counterpart of the feather specimen and its exquisite detail, looking just like a feather found today. When a rock is split open to discover a fossil and the excitement settles, one sees, hopefully, two fossils, one on each side of the split rock. The slab (*Flinz*) contains the bony fossil parts and the finely bedded, more clay- and mud-rich counter-slab (*Faüle*) holds the mould or impression of the organism. Usually, the soft tissues and feathers are best preserved on the counter-slab (Fig. 1.2).

Figure 1.2 The Feather (length 60mm) (MD).

The Munich Specimen

This superbly preserved *Archaeopteryx* fossil skeleton was found at Langenaltheim, to the west of Solnhofen. The skeleton is nearly complete, demonstrating most of its articulation. The specimen that we saw at the Munich Museum was the counter-slab, with evident feather impressions emanating from the limbs. (The Munich Museum actually has both 'part' and 'counterpart', but only the counterpart was in residence during our visit, as the part was on loan to the Solnhofen Museum.)

Figure 1.3 The Munich Specimen seen in the museum store — this is the counter-slab or Faüle *slab; note feather impressions (slab width* c. *300mm (MD).*

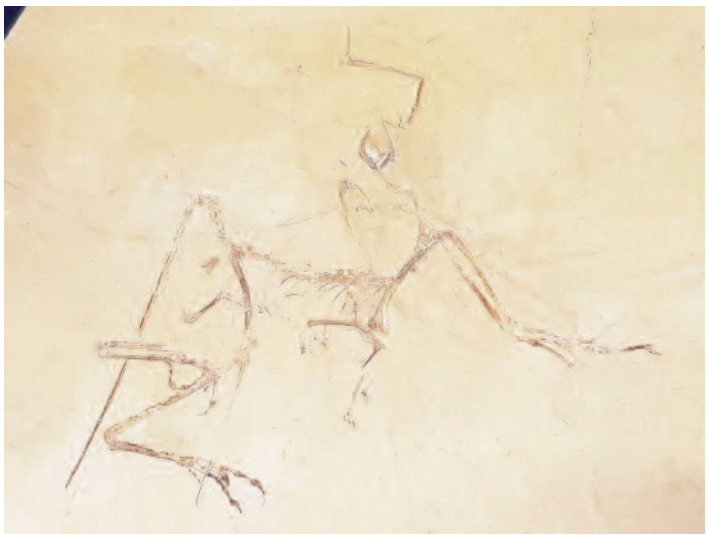


Figure 1.4 The Munich Specimen, professional photograph, Wikimedia Commons — this is the Flintz *slab [thus the mirrored image — Ed.] (Luidger 2005).*

Figure 1.3 shows little detail of the 300mm fossil, but the size of the skull and brain capsule shows that 'birds' had large brains, similar to modern birds, from early in their evolution, which enabled complex flight. Like all the specimens, it shows both reptilian features — such as jaws with sharp teeth and a long bony tail; and avian characteristics — such as a strong furcula (wishbone) on the front of the chest for the attachment of flight muscles, and also wings with asymmetric flight feathers (Fig. 1.4, *previous page*).

This specimen was initially postulated to be a different species (*Archaeopteryx bavarica*), but is now considered to be a juvenile of the species *A. lithographica*. It was sold to the museum for DM2,000,000 in 1999, equivalent to about £1,000,000.

Compsognathus

This small predatory theropod dinosaur is the only terrestrial dinosaur fossil find from the Solnhofen Limestone. Of interest, a skeleton of a small lizard has been found within its stomach (Fig. 1.5). Its lunch was fatally interrupted 150 million years ago!

Alcmonavis poeschli

Dr Rauhut showed us this most recent find, which has thrown the 'first bird' story into a pickle once again. But palaeontologists love a fossil conundrum to disentangle until another specimen throws the cladogram (postulated or computer-generated evolutionary tree) into doubt once more. All but one of the other *Archaeopteryx* specimens come from the Altmühltal Formation of the Solnhofen Limestone, but *A. poeschli* (Fig. 1.6), the right wing of a bird-like species, was found in the younger Mörnsheim Formation. Detailed examination of muscle attachments has shown that is has more derived characteristics than the earlier *Archaeopteryx* fossils, which suggest that it was more able to flap its wings actively for powered flight. This supports the theory of 'ground up' evolution of flight rather than 'tree down' gliding flight initially. Perhaps another specimen will refute this? This specimen was named *Alcmonavis poeschli*, after the old Celtic name '*Alcmona*' for the Altmühl tributary river and the Roman name '*Alchmona*' for the region; plus '*avis*', after the Latin for 'bird'; and Roland Pöschl (who found the fossil) (Rauhut *et al.* 2019).

Figure 1.5 Compsognathus *(slab width* c. *300mm) (MD).*

It is now thought that there was a great diversity of early bird-like creatures (avialans) in the Upper Jurassic. It would have been a magnificent sight in Bavaria 150 million years ago. The paper describing *A. poeschli*, and placing it at the base of the *Avialae*, just above *Archaeopteryx* in the evolutionary tree (Rauhut *et al.* 2019), was published on the same day that we visited the Munich Museum. We were privileged to have Dr Rauhut's personal tour of the storeroom, in between his press commitments.

We were also able to browse the museum's public collection.

Every good story needs some intrigue and the world of the highly prized *Archaeopteryx* fossils doesn't disappoint. The finding of *Archaeopteryx* fossils presented a challenge to the Victorian establishment, some of whom doubted Charles Darwin's 'Theory of Evolution' (to paraphrase the original title). The first full skeleton fossil was found in 1861 (although missing the skull) and Andreas Wagner, the Munich Professor of Palaeontology, could not be persuaded to buy the specimen, as he held strong creationist views and did not accept that the fossil could represent an intermediate form of reptile/bird creature. He thought it was a reptile or saurian. Albert Oppel, who was Wagner's assistant in the Munich Museum, understood its importance and made a sketch from memory, showing its detailed feather-like structures (Fig. 1.7, *opposite*).

Oppel's sketch failed to persuade the Munich Museum to purchase the skeleton, and meanwhile Richard Owen, from the then British Museum of London, negotiated a deal to purchase the specimen (which later became known as the 'London Specimen'), as part of a large collection of Solnhofen fossils. The Feather went to Berlin and its counterpart went to Munich, where we saw it.

Figure 1.6 Archaeopteryx *No. 13:* Alcmonavis poeschli *(slab width* c. *200mm) (MD).*

Figure 1.7 A drawing of the London Specimen by Albert Oppel (MD).

The 1861 find had pushed back the origin of birds from *c.* 30Ma to *c*. 150Ma, and caused quite a stir. Heady days in the palaeontological world indeed (Wellnhofer 2009)!

It was a fascinating day, including a walk back through Munich, which, with its *Führerbauten* or *Führer*-buildings, was declared the 'Capital of the Nazi Movement' in 1935. Some of the headquarters buildings have been demolished, but the impact remains. From Munich we drove north to the ancient town of Eichstätt in the Altmühltal, where the majority of our field time would be spent.

Day 2, Wednesday 15 May: the Solnhofen area

Linda Fowler

On our first day in the Solnhofen area we drove along the Altmühl Valley to the town of Solnhofen itself, to visit the Bürgermeister Müller Museum with Dr Martin Röper, the Curator. Lunch was also in Solnhofen, at the Alte Schule Biergarten, on Dr Röper's recommendation. A photograph of Eduard Opitsch's gravestone is published in Wellnhofer (2009). As Dr Röper himself had not seen Opitsch's grave, he accompanied us first to Langenaltheim to see it with us, before we went to the Haardt Quarry for collecting in the Solnhofen Formation and a small collectors' quarry in the Mörnsheim Formation.

The Altmühltal

It is 27km from Eichstätt to Solnhofen via the Altmühl Valley and we were able to see white crags along the valley sides (Fig. 2.1). These are remnants of massive microbial and sponge mounds that grew around the Jurassic reefs, edging the deeper basins where the laminated limestones of the Solnhofen and Mörnsheim formations were deposited (*see* Fig. 0.9). A stop by a road cutting through one of these mounds enabled John to point out some of the finer structure and detail for us to inspect (Fig. 2.2).

Figure 2.1 The Twelve Apostles: dolomitic limestone crags, remnants of sponge and microbial mounds, on the sides of the Altmühl Valley east of Solnhofen (LF).

Figure 2.2 (a) Sponge and microbial mounds (right) with (b) fossil sponge (above right) (LF).

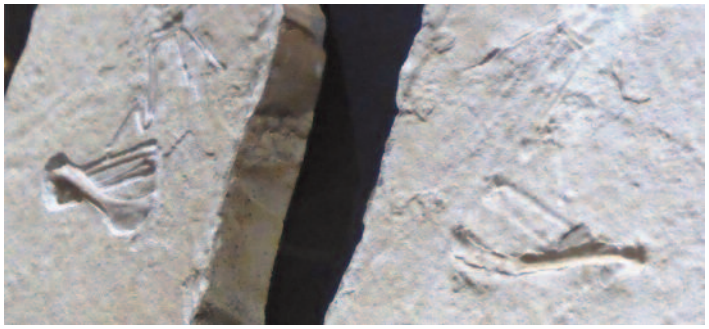


Figure 2.3 (left) The original of Archaeopteryx *No. 6, the Solnhofen Specimen of* Archaeopteryx lithographica*, displayed in the Bürgermeister Müller Museum, Solnhofen (LF).*

Figure 2.4 (above) The original of Archaeopteryx *No. 9, the 'Chicken Wing', Archaeopteryx lithographica, displayed in the Bürgermeister Müller Museum, Solnhofen (LF).*

The Bürgermeister Müller Museum, Solnhofen

Averil Leaver

On Wednesday we met with Dr Martin Röper in Solnhofen and he introduced us to their collection of fossils, which includes two *Archaeopteryx* specimens, the Solnhofen No. 6 (Fig. 2.3) and the 'Chicken Wing' No. 9 (Fig. 2.4).

The museum displays gave us an excellent outline of the environments and circumstances that had enabled the preservation of so many specimens, as the labels were both in German and in English. The little town of Solnhofen has produced a fine museum, which displays a beautiful collection of fossils found in the local area and made them accessible to the public and scientists alike (Fig. 2.5). The upper floor held a display to demonstrate lithographic printing, which used the limestone found in the area and gives its name to *Archaeopteryx* species. We were all delighted by the displays, which were informative and visually attractive.

Later in the day Dr Röper took us to the cemetery in Langenaltheim where Eduard Opitsch is buried (Fig. 2.6, *opposite*). Opitsch was the owner of *Archaeopteryx* No. 3, found in a private quarry he owned in the Langenaltheim/Haardt area. He lent the fossil for a time to the museum we were to visit the following day, formerly known as the Maxberg Museum (*see* Day 3, *below*), which is why No. 3 became known as the 'Maxberg Specimen'. However, Opitsch declined any palaeontological research and, when he attempted to sell the fossil to the museum, he turned the initial offer down hoping for a higher price, and withdrew the specimen from the museum. Martin Röper had been shown the fossil, aged 10, when he visited Opitsch at his home in Pappenheim, but it was missing when Eduard Opitsch died, at the age of 91, in 1991. Copies of the two fossil slabs exist in the Munich Museum. After investigation of these copies of the original find this specimen has been assigned to the *A. lithographica* species. An image is reproduced on Opitsch's gravestone. There is even a suggestion that the original slabs may have been buried with him!

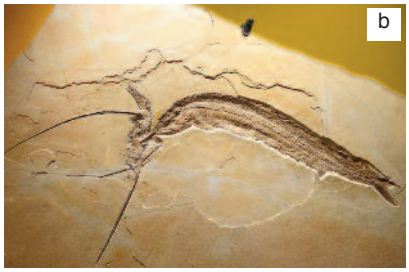


Figure 2.5 Fossils on display at the Bürgermeister Müller Museum in Solnhofen: (a) Predator and prey both succumb to anoxic waters, (b) Arm and crown of archaic squid, (c) Pterodactyl, (d) Saccocoma *(a free-floating crinoid) and squid faeces (AL).*

Figure 2.6 Eduard Opitsch's grave in Langenaltheim Friedhof (AL).

Haardt Quarry
Kath Addison-Scott

After our morning in the exceptional Bürgermeister Müller Museum, and the excellent lunch at the Gaststatte Alte Schule, we spent an hour in the Haardt Quarry (Figs 2.7 and 2.8). We were again accompanied by Dr Martin Röper. This working quarry is in the Solnhofen Formation and so, as this was our first collecting chance, we had high hopes of finding some fossils. You can never tell what might turn up. However, we were only allowed onto the beds below the already worked layers and to rummage in some spoil heaps. Pickings were slim!

We did find lots of samples of manganese dendrites: the manganese oxide crystallises within the limestone, creating branch-like formations. These are dark brown to black patterns in the limestone that look like plant fossils. Some slabs contain 'pictures' that can look like trees and some like hedges. Nothing much seems to be wasted from the quarrying and local craftsmen turn these dendritic slabs into framed pictures and fridge magnets. Figure 2.9 is a superb example as displayed in the Bürgermeister Müller Museum. Many of the fossils from Solnhofen, which are on display in several museums, are surrounded by dendrites.

Figure 2.9 Dendrites on Solnhofen Limestone as displayed in Bürgermeister Müller Museum (KAS).)

Figure 2.7 Haardt Quarry, Solnhofen (KAS).

Figure 2.8 Haardt Quarry, Solnhofen – worked area (KAS).

There were several finds of coprolites (Fig. 2.10a), which are liberally scattered around the area and had landed on the Jurassic seabed. In Figure 2.10b broken spines (probably from a sea urchin) can be seen using a hand lens. Several examples of *Saccocoma* sp. were also found by our OUGS group — *Saccocoma* are floating crinoids and one of Solnhofen's most common fossils (Fig. 2.11, *overleaf*); and also one of the small, bony 'spratlike' fish, *Leptolepides* (Fig. 2.12; found by Linda Fowler, *overleaf*).

Figure 2.10 Coprolites: (a) 42mm long, (b) 15mm long (containing spines) (KAS).

Figure 2.11 (a) Saccocoma *sp. (*c. *12mm across), (b)* Saccocoma *sp. (*c. *12mm across) (KAS).*

Figure 2.12 Leptolepides *from Solnhofen Formation, Haardt Quarry (LF).*

OUGS 'find' at Hobby Steinbruch nr Mörnsheim

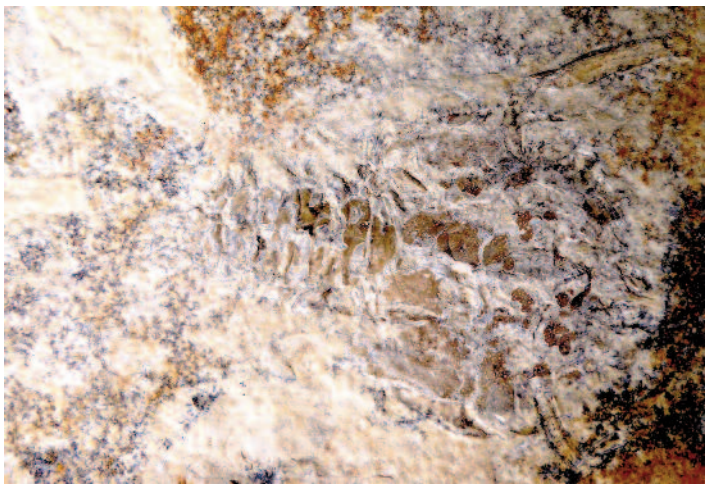
Linda Fowler

Finally Dr Röper took us to a small collectors' quarry in the younger Mörnsheim Formation where one of the group, Terry Blake, found a crustacean, later identified as the first *Eryon cuvieri* that has been found in these younger strata (Fig. 2.13), and donated by Terry to the Bürgermeister Müller Museum so that it can be properly prepared and curated.

Day 3, Thursday 16 May

On our third day we visited the Fossilien und Steindruck Museum (formerly the Maxberg Museum) in Guzenhausen and then went to the Fossilien Besuchersteinbruch Mühlheim in Mörnsheim in the afternoon. We ended the day at the Berger Museum and quarry at Harthof.

Figure 2.13 The first fossil of the crustacean Eryon cuvieri *that has been found in the Mörnsheim Formation (image* c. *150mm wide) (LF).*



Thursday morning

Averil Leaver

At the Fossilien und Steindruck Museum we saw some of the uses to which the limestone has been put over the centuries. This included a reconstruction of a Roman wall and paving that had been excavated in the locality (Fig. 3.1) and also impressive Rococo paving at Ottobüren Monastery (Fig. 3.2).

The fossil collection was exceptional. The fossils were well prepared and beautifully presented. The key exhibit for us was the large assembly of many of the specimens of *Archaeopteryx*, early birds and rare dinosaurs found in the local limestone, albeit that many of the *Archaeopteryx* 'fossils' were casts, including the now missing Maxberg Specimen (*see* Day 2, *above*) (Fig. 3.3, *opposite*).

It is reassuring to know that the Bavarian State, local authorities and non-profit-making associations are investing in museums and specimens to illustrate the rich geological and cultural heritage of the area.

Der Limes um 100 nach Chr.
Unser Gebiet zur Römerzeit
Kastell, Lager, Kastellbad
Römisches Kastellbad in Theilenhofen vor 1700 Jahren

Figure 3.1 Reconstruction of a Roman wall and paving in the Fossilien und Steindruck Museum, Guzenhausen (LF).

Figure 3.2 Reconstruction of the Rococo style floor in the Imperial Chamber at Ottobüren Monastery (AL).

Other uses of Solnhofen Limestone

Linda Fowler

These include intricate carvings, making use of natural grey and cream colouration in the stone, and features such as Liesegang rings (Fig. 3.4, *opposite*) and the traditional lithographic printing for which this very fine-grained stone is famed (Fig. 3.5, *opposite*.)

Figure 3.3 Fossilien und Steindruck Museum fossil display, including (below) a copy of the missing Maxberg Specimen No. 3 (H. Raab (UserVesta) — own work, CC BY-SA 3.0, https://commons.wikimedia.orgwindex.phpcurid=8336374).

Figure 3.4 The Dangolsheim Madonna, a semi-relief in Solnhofen Limestone by Josef Bernhart of Munich (LF).

Figure 3.5 (a) A lithographic slab ready to print wrappers for tins of Portuguese sardines and (b) bank notes, playing cards and match-box labels are some of the items printed by lithography (LF).

Figure 3.6 Filming the launch of Alcmonavis poeschli *at Mühlheim Quarry. From left to right: Roland Pöschl (finder), woman not known, Oliver Rauhut (author), Uli Leonhardt (quarry owner) (LF).*

Afternoon: Fossil Besuchersteinbruch, Mühlheim

We visited the Fossilien Besuchersteinbruch (visitor quarry) Mühlheim, where we were able to eat our lunch and hunt for fossils in the younger Mörnsheim Formation (*see* Fig. 0.8). This is the locality where Roland Pöschl recently found the newly described *Alcmonavis poeschli*, and a highlight of our afternoon was to see Bavarian Television filming the 'launch' of this find (Fig. 3.6).

The quarry, like others in the area, is well set up for amateur fossil hunters with hammers and goggles for hire, and useful information boards (Fig. 3.7), providing a safe and educational environment enjoyed by adults and children alike. We finished the day with a further museum and quarry visit at the Berger Museum, Harthof.

Day 4, Friday 17 May: Nördlingen and Ries Crater

Norman Nimmo-Smith

We spent Friday visiting the Ries impact crater. Although our visit to southern Germany was primarily a palaeontology trip with a focus on the dinosaur-like bird *Archaeopteryx*, the Ries Crater was not far from our base at the town of Eichstätt, and our leader Dr John Nudds had wisely included it in his itinerary. During the day we visited two quarries and the town of Nördlingen, which sits inside the crater itself.

The Ries Crater formed *c.* 14.5 million years ago in the Neogene Period as a result of an asteroid impact. The asteroid had an estimated diameter of *c.* 1km and the impact formed a crater 25km in diameter, destroying all life within a radius of >100km. Once the dust had settled (following rebound of basement rocks, collapse of the crater walls and deposition of fall-out material), a 400m deep basin remained inside the crater. This gradually filled with water to form a lake, which eventually silted up over a period of *c.* 2Ma, leaving a flat plain inside the crater. Today the crater's outer rim is marked by a low ridge, up to 150m high and clearly visible in the landscape.

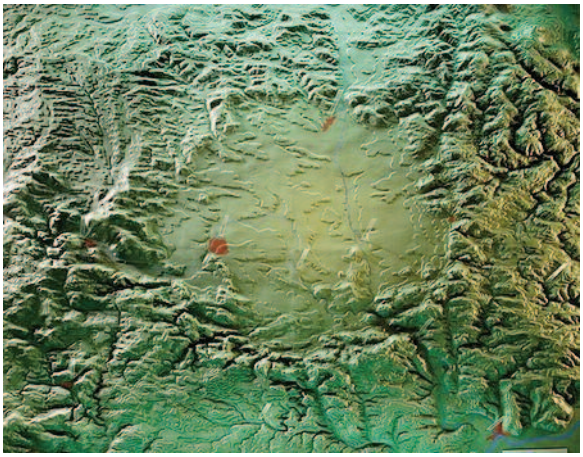
The museum in Nördlingen displays a model of the Ries Crater, which shows the infilled crater bowl and elevated landscape of the outer crater rim (Fig. 4.1; the red dot inside the crater at the lower left shows the location of Nördlingen). The geological map of the area also shows the crater outline clearly (Fig. 4.2).

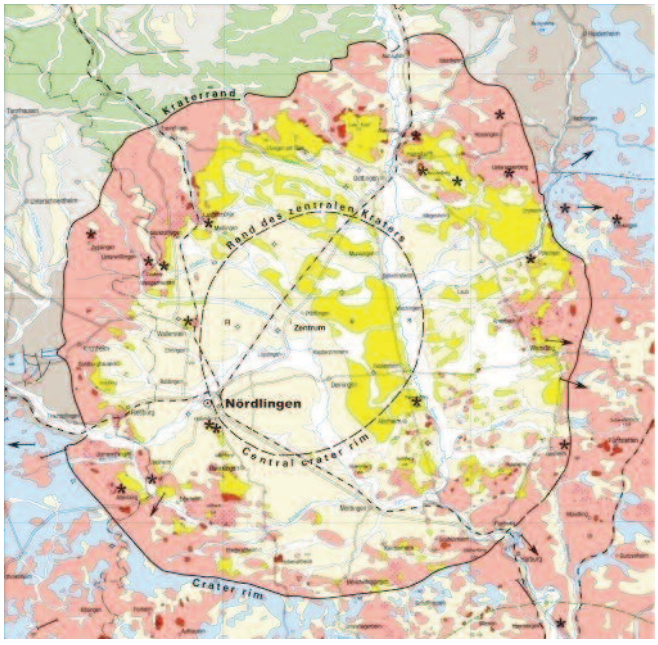
Figure 3.7 The Fossil Visitor Quarry, Mühlheim, has information boards sponsored by local businesses (LF).

The asteroid impact created two types of rock: Bunte Breccia and suevite. The Bunte Breccia is a chaotic mixture of rock fragments of different colours, originating from different bedrock formations that were ejected during the impact ('*Bunte*' = colourful).

Figure 4.1 The Ries crater model on display at the Ries Crater Museum in Nördlingen (NN-S).

Figure 4.2 Geological map (Bavarian State Office for the Environment). The pink colour indicates impact breccia, and yellow/beige indicates sedimentary crater fillings (NN-S).





The ejecta formed a blanket deposit across the surrounding area. Suevite is a so-called impact breccia that formed from the hot debris cloud that rose into the air before falling back into the crater on top of the Bunte Breccia. As the melt cooled, a rock with glass inclusions was formed. The enormous pressures and extremely high temperatures during the impact also formed very small diamonds in the suevite from graphite-bearing gneiss in the crystalline bedrock. However, the concentration of diamond is too low for commercial exploitation. (The name suevite is from the Roman name, Suevia, for Swabia, this region of Bavaria, linking the Ries Crater description firmly to the history of crater research — LF).

Aumühle Quarry

Our first stop of the day at Aumühle Quarry enabled us to examine both rock types. This quarry is situated inside the crater rim near the town of Oettingen. The sharp contact between the grey-coloured suevite and brown Bunte Breccia was clearly visible on one section of the quarry face (Fig. 4.3). It is estimated that the final crater had formed and all deposition had ceased within 10 minutes of the impact. When we examined the weathered Bunte Breccia we found that it has a texture similar to clay and readily crumbled into small pieces. The suevite on the other hand was a fairly hard and homogeneous rock without indications of sorting or bedding (Fig. 4.4).

Figure 4.5 Plan of Nördlingen's historical old town (NN-S).

The Ries Crater was long thought to have a volcanic origin, and it was not until the 1960s that analysis of the suevite by Eugene Shoemaker and Edward Chao confirmed the impact theory (Shoemaker and Chao 1961). Rock from Otting Quarry, which we visited later in the day, was found to contain high-pressure forms of quartz (coesite and stishovite) that could not have been formed by the temperatures and pressures of terrestrial geological processes. Shoemaker and Chao had previously found coesite at another impact site, the Barringer Crater (also known as Meteor Crater) in Arizona, USA.

Nördlingen and the Ries Crater Museum

We continued on to Nördlingen, an old medieval town encircled by well preserved walls with towers and covered parapet paths (Fig. 4.5). We walked through one of the old city gates and made our way to the Ries Crater Museum in the aptly named 'Eugene Shoemaker Platz'.

The museum had superb exhibits showing the geological history of the Ries Crater — these described events before, during and after the impact. There were many rock specimens to examine as well, including a piece of Moon rock brought back to Earth by the astronauts of Apollo 16 (Fig. 4.6). Apollo astronauts visited the Ries Crater to study the rocks there as part of their training for

Figure 4.6 Moon rock on display at the Ries Crater Museum, Nördlingen (NN-S).

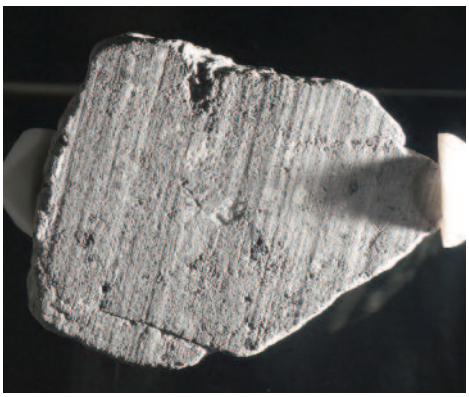


Figure 4.3 (left above) Exposure in Aumühle Quarry showing grey coloured suevite in contact with brown Bunte Breccia (NN-S).
Figure 4.4 (left below) Suevite in Aumühle Quarry is unsorted and displays no bedding (NN-S).

Figure 4.7 Tower of St Georgskirche, Nördlingen (NN-S).

Figure 4.8 Dressed suevite block with black, glassy clasts. St Georgskirche, Nördlingen (NN-S).

Figure 4.9 Nördlingen town centre and the distant crater rim, looking south-east from the tower of the St Georgskirche (NN-S).

Figure 4.10 Exposure of suevite at Otting Quarry (face c. *4m high) (NN-S).*

their landing on the Moon and, in recognition of the importance of the Ries Crater in preparation for the Moon mission, NASA presented the Moon rock to Nördlingen. It is an impact breccia from the Moon's highland area and is very similar to the Ries suevite.

After the museum visit, we had some free time to have lunch and enjoy the sights of Nördlingen. The dominant St Georgskirche at the centre of the old town (Fig. 4.7) was built using suevite from a nearby quarry, and black glass clasts in the suevite were clearly visible in many of the dressed blocks (Fig. 4.8). Some of us climbed the 350 or so steps to the viewing tower at the top of the church, and from the top there were spectacular, uninterrupted panoramic views across the town rooftops to the outer rim of the crater in the distance (Fig. 4.9).

Our final destination was the largest suevite quarry, now disused and overgrown, located at Otting, *c.* 6km east of Wemding. The Otting Quarry had long been the source of suevite, which had been used as a building material in this region of Bavaria since Roman times; and in the 18th century it was also discovered to be a suitable binding agent for mortar and cement. In an exposure near the entrance we were able to examine some suevite blocks that were lying around at the base of the quarry face (Fig. 4.10). Unlike the suevite quarry

we had visited earlier in the day at Aumühle, the Otting Quarry lies outside the crater rim. This demonstrated that suevite ejecta travelled considerable distances before deposition. Suevite from the Otting Quarry is particularly glass-rich, and the glass contains vesicles.

Clasts in suevite

Linda Fowler

Travelling from Nördlingen to Otting Quarry, we regrouped by Otting Rathaus, where we found a beautiful 1.5m boulder of suevite, presenting us with an opportunity to examine its fresh surface for the variety of interesting clasts to be found. Some of these are black and glassy, with vesicles (as mentioned above) and many of these show plastic deformation (Fig. 4.11). The explanation is that gneissose material was excavated and melted from the crystalline basement by the impact, and exsolving gases expanded, creating vesicles. Other clasts contain remnants of gneiss along with glass (Fig. 4.12), and some have glassy rims (Fig. 4.13), either where melt aggregated around the igneous rock, or where the outer surface was melted (Ernstson and Kord n.d.). It is easy to see how this deposit was mistaken for volcanic ignimbrite containing lower crustal material before Shoemaker and Chao discovered the coesite evidence.

Ries Crater: impact and later history

Joyce Ali

Many details of this important event, *c.* 15Ma, have been fully recorded, and give an exact sequence and step-by-step account of the complicated end results, seen especially in many local quarries. The guidebook from the museum (Poesges and Schieber 2015) is very informative, and explains how the devastated landscapes survived, evolved and changed to create the present topography. The back cover of the book has a striking image of a 'patchwork' of higher green areas and a network of drainage channels and smaller watercourses in the lower part.

The impact

The rocks outcropping in the area when the impact occurred were Upper Jurassic and Triassic, underlain by crystalline basement. Heat and high-pressure waves from the impact devastated a large area of the surrounding countryside. Vegetation would have been set on fire, flattened and destroyed. Charred timbers and vegetation have been found over a wide area. Large limestone boulders landed many kilometres away from the crater, and polished sheets of Jurassic limestone with glacial-type striations from impact material show directions radiating from the central area. Moldavites (tektites), the blue-green glassy fragments, are thought to be derived from Tertiary clayey sands from the upper freshwater molasse, and were transformed by the impact; these are now found in sediments and river deposits throughout Bohemia, Moravia and upper Austria. The impact shocked the crystalline basement rocks, creating suevite of two main types: the main mass is a 300m thickness of crater 'fall-back' suevite in the central area; and there are also patches of outer 'fall-out' suevite around the crater rim and outside the crater. The rocks at the impact site were reduced to rubble and clouds of dust and ash rising high in the air fell over a large area.

Figure 4.11 (top) Molten lower crustal material has been deformed plastically and incorporated into suevite. Boulder by Otting Rathaus.
Figure 4.12 (middle) Basement gneiss partially molten and incorporated into suevite. Boulder by Otting Rathaus.
Figure 4.13 (bottom) Clast with glassy material around its rim. Boulder by Otting Rathaus (Figs 4.11, 4.12 and 4.13 LF).

Evolution of the crater lake(s)

The crater initially housed a lake, and vast amounts of mud and debris were washed into this basin, forming layers up to 50m thick. The lake would have stayed warm, muddy and salty for a long time, and perhaps as many as 100 years passed before fish and plants that were able to cope with the saline conditions were able to inhabit the lake. Fossil specimens have been identified in lake limestones. High temperatures and evaporation rates produced the salty waters and local plant material is found in sediments. In winter seasons rain replenished water levels and expanded the lake's size, but gradually debris washed in and silted up the basin. Red and brown algae, insect larvae and salt marsh plants began to inhabit , similar to what we can see in soda lakes found in arid environments today. Clay and marl layers, some up to 100m thick, have been found from this period. A change in climate altered lake conditions, bringing fresh water where diatoms began to spread. Vegetation began to grow around the lakes, which continued to silt up, although some erosion channels drained areas and made them dry. At its maximum height the dry lake floor is calculated to have reached 100m above today's land surface inside the crater.

Water catchments, drainage and present-day topography

Large areas of the drainage and rain catchment areas in the west, north and east were affected, obliterating the outlines and signs of the crater's structure, making the Upper Jurassic cuesta [a hill or ridge sloping gently on one side — Ed.] blend in with land to the south. The course of the Wornitz River was altered to flow south, which reactivated the trench where the earlier 'proto-Danube' would eventually be reinstated. The Wornitz and the Eger rivers slowly excavated the soft marls and clay, eventually revealing the outlines of the impact crater structure.

The last major event was the Ice Ages, between 2.5 million and 10,000 years ago. Cold and warm periods during this time left different traces as various river muds, river gravels and aeolian deposits (loess and wind-blown sands) alternated. This is still evident in today's landscape, as the loess produces fertile soil, while the sands are less useful. Animals adapted to the colder climate have left remains, including cave bear, wild horse, prairie elephant and mammoth. Evidence of human habitation back to the Palaeolithic has been found here.

The events following this major impact were interesting to explore and provided a benchmark for comparison with similar geological sites. It is a fine example of how work done in a relatively short time can present a clear picture of this exceptional event.

Day 5, Saturday 18 May: Altmühltal Dinosaur Park and Gerstner Quarry

Norman Nimmo-Smith

Our final day of the trip took us eastwards from our base at Eichstätt towards the town of Denkendorf. The plan was to visit the Altmühltal Dinosaur Park situated 2km north of Denkendorf, where we would see the original specimens of *Archaeopteryx* Nos. 8 and 12, and then drive *c.* 12km farther east to the quarry near the village of Schamhaupten where No. 12 was found in 2010.

The Altmühltal Dinosaur Park (Fig. 5.1) is a large tourist attraction, with a restaurant, beer garden, shop, two museum halls and a 1.5km trail through woods where there are more than 70 life-size models of dinosaurs and other prehistoric animals.

Figure 5.1 Outside the restaurant at Altmühltal Dinosaur Park where other creatures were also feeding (NN-S).

We started our visit at the main museum hall, which displayed a large number of fossils, including pterosaurs, fish, dragonflies and crustaceans as well as a juvenile *Tyrannosaurus rex*. We quickly spotted the display area for *Archaeopteryx* No. 8 near the entrance (Fig. 5.2). This specimen was found in limestone of the Mörnsheim Formation and is thus younger than all the other *Archaeopteryx* specimens (these mostly came from the underlying Solnhofen Limestone). *Archaeopteryx* No. 8 (known as the 'Daiting Specimen') was discovered in the 1990 (Fig. 5.3). The skeleton of this specimen is incomplete, with only the upper (anterior) half of the skeleton preserved. Note the cut marks on the lower bones where material was removed for analysis.

CHAEOPTERYX ALBERSDOERFERI, DER JÜNGSTE URVOGEL
ARCHAEOPTERYX ALBERSDOERFERI, THE YOUNGEST URVOGEL
ach dem Mitbegründer des Dinosaurier Museums Raimund Albersdörfer

Figure 5.2 Leader John Nudds in front of the display board describing the work he and a number of colleagues had carried out on Archaeopteryx *No. 8 (NN-S).*

Figure 5.3 The incomplete skeleton of Archaeopteryx *No. 8 with its skull on the left (image width 180mm) (NN-S).*

Figure 5.4 Archaeopteryx *No. 12, the Schamhaupten Specimen (image width 34mm) (NN-S).*

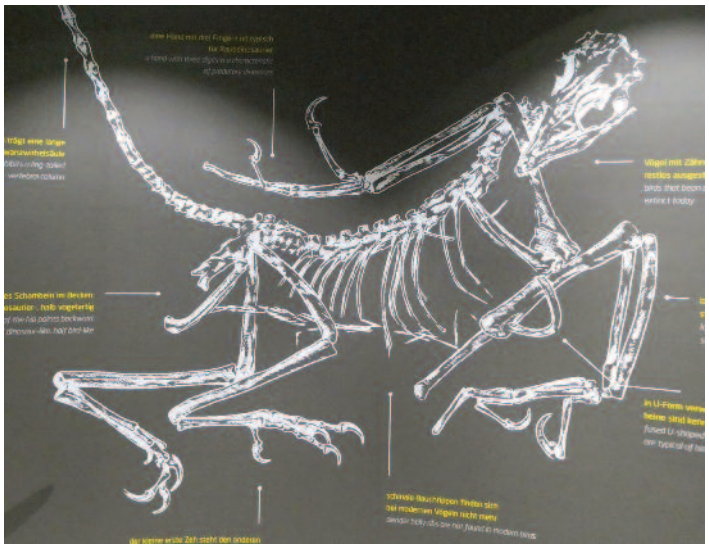


Figure 5.5 Museum drawing of Archaeopteryx *No. 12 (NN-S).*

Our leader, Dr John Nudds, described its history and the work he and a number of colleagues had carried out on it, which was published in 2018. During the study the team used high-resolution synchrotron micro-tomography to perform a 'virtual dissection' of the specimen. Images from their paper on this research were reproduced on the museum's display board (*see* Fig. 5.2). Geochemical analysis of limestone from the Daiting Specimen showed it to be the youngest of all known Bavarian *Archaeopteryx* fossils by up to 400,000 years. The study also showed that it had a number of more advanced skeletal features than similar-sized (and older) *Archaeopteryx* specimens, indicating that it very probably had an enhanced capacity for aerial travel (whether gliding or flapping) compared with previous *Archaeopteryx* specimens, and has been described as a new species, *A. albersdoerferi*, by Dr Nudds and his colleagues.

Archaeopteryx No. 12 (known as the 'Schamhaupten Specimen') was the main exhibit in a separate building at the museum. Unlike *Archaeopteryx* No. 8, this specimen is almost complete (Fig. 5.4), although no feathers had been preserved; No. 12 is the oldest *Archaeopteryx* found so far and was discovered in the Painten Formation, which underlies the Solnhofen Formation. A drawing on the adjacent information board helped us to identify the different skeletal parts (Fig. 5.5). It was discovered by a fossil collector at the Gerstner Quarry near Schamhaupten and was described by Dr Oliver Rauhut, whom we had met at the museum in Munich on Day 1 of the trip (Rauhut *et al.* 2018).

The largest exhibit in the museum was the skeleton of a juvenile *Tyrannosaurus rex*, known as 'Rocky' (Fig. 5.6), who had grown to a length of 10m before perishing. Rocky lived in what is now South Dakota, USA, in the Upper Cretaceous Period. John Nudds observed that Rocky was actually a female! Apparently, the gender can be determined by the relative length of particular bones at the base of the tail. There were also many other well

Figure 5.6 Juvenile Tyrannosaurus rex *in the museum at Altmühltal Dinosaur Park (Sue for scale) (NN-S).*

Figure 5.7 Bony fish Liodesmus *from the Solnhofen Limestone (image width 300mm) (NN-S).*

Figure 5.8 Shrimp Aeger *from the Solnhofen Limestone (image width 200mm) (NN-S).*

preserved fossils on display from the Upper Jurassic lagoonal Solnhofen Limestone (Figs 5.7, 5.8 and 5.9).

After completing our tour of the museum, we set off along the woodland trail to find the 70 life-size models of prehistoric animals. The trail was laid out on a timeline from the Triassic to the Neogene, with models of creatures appropriate for the time set at intervals along the way (Figs 5.10, 5.11 and 5.12, *opposite*). We all had lunch in the sunshine at the beer garden conveniently located part-way along the trail among the trees.

Following our visit to the Altmühltal Dinosaur Park, we drove *c.* 12km to the Gerstner Quarry, situated in the countryside near the village of Schamhaupten. This is a public quarry provided by the rural district of Eichstätt for fossil collectors (Fig. 5.13, *opposite*), and we spent a pleasant time breaking open limestone blocks in the hope of finding something interesting. But alas, despite hammering for ages nothing noteworthy was found.

When we arrived at the quarry, we noticed that part of it was fenced off and that two 'professional' collectors were busy extracting limestone blocks from a pit and splitting them open in search of fossils (Fig. 5.14, *opposite*). While we were there, they 'struck lucky' and found a large fish inside one of the limestone blocks, which they kindly showed us (Fig. 5.15, *opposite*). According to one of the collectors such finds are rare, so we were rather fortunate to have been there when it was found. They also confirmed that *Archaeopteryx* No. 12 was discovered in the pit they were continuing to excavate.

After yet another fun-packed day we headed back to Eichstätt and our final group dinner at the Trompete Inn (Fig. 5.16, *opposite*), where, as a final thank-you, Jan presented John Nudds with the classic book on *Archaeopteryx*, written by Peter Wellnhofer (Wellnhofer 2009).

Figure 5.9 Dragonfly Stenophlebia *from the Solnhofen Limestone (image width 180mm) (NN-S).*

Many thanks to John Nudds (University of Manchester) and to Cindy Howells (National Museum of Wales, Cardiff) for their informative and friendly guidance around the area, and also to Jan Ashton-Jones for organising us all. It was a memorable trip.

References

Ernstson, K., and Kord, F. [n.d.] (on-line) 'The Ries crater impactites'. http://www.impact-structures.com/impact-germany/the-ries-impact-structure-germany/the-ries-impactites/ (accessed 29 August 2019)

Kundrát, M., Nudds, J., Kear, B. P., Lü, J., and Ahlberg, P. 2019 'The first specimen of *Archaeopteryx* from the Upper Jurassic Mörnsheim Formation of Germany'. *Hist Biol* **31**, 3–63; doi.org/10.1080/08912963.2018.1518443

Nudds, J., and Howells, C. 2019 *Archaeopteryx and the Solnhofen Limestone*. Handbook produced for the field trip

Luidger [author has no initials — Ed.] 2005 (on-line) 'File: *Archaeopteryx* bavarica detail'. https://commons.wikimedia.org/wiki/File:Archaeopteryx_bavarica_Detail.jpg (accessed 1 September 2019)

Poesges, G., and Schieber, M. 2015 (on-line) 'The Ries Crater Museum, Nordlingen' (2nd edn). Verlag Dr Friedrich Pheil https://pfeil-verlag.de/publikationen/the-ries-crater-museum-noerdlingen/

Rauhut, O. W. M., Foth, C., and Tischlinger, H. 2018 'The oldest *Archaeopteryx* (Theropoda: Avialiae): a new specimen from the Kimmeridgian/Tithonian boundary of Schamhaupten, Bavaria'. *Peer J [J Life and Environm Sci]* [for] 2018, 1–101; doi.org/10.7717/peerj.4191

Rauhut, O. W., Tischlinger, H., and Foth, C. 2019 'A non-archaeopterygid avialan theropod from the Late Jurassic of southern Germany', *eLife* **8**, 1–38; doi.org/10.7554/eLife.43789

Scotese, C. R. 2002 (on-line) PALAEOMAP website. http://www.scotese.com (accessed 6 September 2019)

Selden, P., and Nudds, J. 2012 'The Solnhofen Limestone', *in* Selden, P., and Nudds, J. (eds) *Evolution of Fossil Ecosystems* (2nd edn). London: Manson, 156–67

Selden, P., and Nudds, J. (eds) *Evolution of Fossil Ecosystems* (2nd edn). London: Manson

Shoemaker, E. M., and Chao, E. C. T. 1961 'New evidence for the impact origin of the Ries Basin, Bavaria, Germany'. *J Geophys Res* **66**, 3371–8; doi.org/10.1029/JZ066i010p03371

Stiegler, J. 2006 (on-line) 'Solnhofener Steinbruch Frauenberg' https://commons.m.wikimedia.org/wiki/File:Solnhofener_Steinbruch_Frauenberg.jpg#mw-jump-to-license (accessed 20 January 2020)

Tang, C. M. 2013 (on-line) 'Tithonian Stage'. https://www.britannica.com/science/Tithonian-Stage (accessed 1 September 2019)

Wellnhofer, P. 2009 *Archaeopteryx — the Icon of Evolution*. Verlag Dr Friedrich Pheil (December 17, 2008)

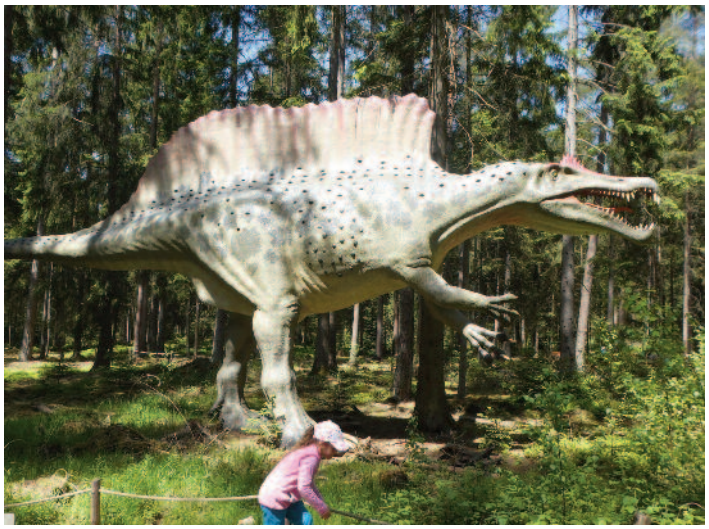


Figure 5.10 (top) Fish-eating Spinosaurus *from the Lower Cretaceous lumbering through the trees at Altmühltal Dinosaur Park (NN-S).*
Figure 5.11 (middle) A mature Tyrannosaurus rex *from the Upper Cretaceous (people beneath tail for scale) (NN-S).*
Figure 5.12 (bottom) 2m-long Velociraptors (with feathers) from the Upper Cretaceous scampering through the trees (NN-S).

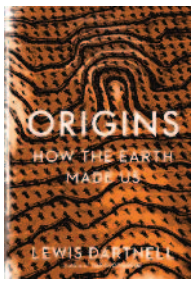
Figure 5.13 Gerstner Quarry near Schamhaupten where Archaeopteryx *No. 12 was found in 2010 (NN-S).*

Figure 5.14 Collector at Gerstner Quarry splitting limestone blocks in search of fossils (NN-S).

Figure 5.15 Freshly-exposed fossil fish discovered while we were at Gerstner quarry (€2 coin for scale) (NN-S).

Figure 5.16 Trompete Inn at Eichstätt, where we enjoyed our final group dinner (NN-S).

Book review



Dartnell, Lewis 2018 *Origins: How the Earth Made Us*. London: The Bodley Head (ISBN 978-1-847-92435-3; 346 pp; hardback £20)

Origins is the book I would want to have written myself. This assertion is far from intending to level (up!) to the ingenuity by the author and the breadth of knowledge required to write such a book. It is simply that these pages compile a very satisfying account to quench a geologist's lifelong curiosity on linking geology with history. There you have it; a confession that shows my partiality about the book's contents, weakening the scientific/editorial mind I would rather approach with and apply to this review. With this caveat out of the way, consider yourself warned!

Reading *Origins* has offered me a wealth of information that has enriched my understanding of history; or rather, it has opened the path to a new discipline to explore. Because, let's not forget, this is a book on the history of humankind from the evolutive processes that led to the hominins who created Palaeolithic cultures as our prehistory and our history to the present day. However, unlike many other history books, which leave out most of the juicy bits that would tantalise a geologist, *Origins* puts the Earth, its geological processes and environments as the root cause for the effects that shaped our trajectory as a species.

It does this in a rather astonishing (and sometimes incredible) way. Prof. Dartnell expands on what other authors such as Prof. Richard Fortey and Simon Winchester explored with books such as *The Earth* and *The Map the Changed the World*, respectively (to name a few). Dartnell pieces together a chronological, but not necessarily progressive, account from the dawn of humanity to the contemporary challenges we face nowadays. I say a chronological account, but as you read the book you come to expect plenty of detours amid a story in any chapter, to bring you back to events as distant as the explosion of a supernova or the formation of the Solar System to help set the reader in the correct scientific mindset. Unfortunately, it also brings about excessive recapping, perhaps unnecessary for those who know the various scientific subjects well. Popular science isn't written to reach scientists after all — or so says a friend of the OUGS I mention later on!

What derives from this comment about digressions is that one doesn't need to be a geologist (or a scientist by default) to enjoy this book. Furthermore, because geological processes are well explained for non-geologists, *Origins* also poses as a book with the potential to help general readers to perceive geology (and the 'nutters' who study it!) with a positive new understanding. Hope is the last thing to lose, right?

Please, gift this book to family and friends!

For those who have a decent foundation in Earth Sciences, as we do in the OUGS, the book helps to perceive 'geo-history' as a riveting subject to delve into more deeply. Please note that I say geo-history. That's right; that's my point. As an early enquirer into Earth's mysteries, into its rocks and landscapes, I soon grew interested in how geography and geology conditioned our world, us inhabitants and our lives. It was fun to compare places, cultures and customs from the point of view of the underlying geology; a perception that I soon noticed not everyone around me was aware of (or interested in!). Therefore, as I read the book, I confided these thoughts to my private musings.

Then came about the showing of TV documentaries such as Prof. Iain Stewart's How *Earth Made Us*, resulting in an entertaining and justified presentation of the subject matter that allows us geologists to be pleased. Prof. Stewart is both an academic Earth Scientist and a science communicator — he is the Chair in Geoscience Communication at the University of Plymouth; and he is an OUGS friend and *Proceedings* author. Just as Prof. Stewart is an academic in science communication, the author of *Origins* is also an academic in science communication at the University of Westminster, but in his case with academic credentials as a Biologist. Prof. Dartnell's life sciences background is also evident in *Origins*, with a dedicated chapter to our biological makeup, and with biological explanations sprinkled throughout his text. This multi-disciplinary approach to history, however, covers much more: there are almost 300 pages divided into nine chapters dedicated to exploring 'how the Earth made us' that take into account complicated socio-eco-political implications. It is an enticing read and it leads to the feeling of having a personal quest fulfilled. Therefore, I am willing to accept, even justify, Dartnell's somewhat pervasive 'show off' attitude that oozes throughout the book.

There is no doubt that Prof. Dartnell did exhaustive and detailed research in preparing to write this book — the book has two substantial 'Notes' and 'Bibliography' sections, and an index that compares to that of a textbook. His skilful art of a storyteller is, however, interrupted with frequent (and long!) footnotes that could have been absorbed in the text; or omitted, as some of the information in the notes does not really seem necessary.

Without further ado, I leave it to the curious reader to discover the stories, those 'oh!' and 'of course!' exclamations, the a-ha moments and, yes, the far-fetched explanations that just seem too…, let us say, convoluted? For example, what does the Cretaceous Period have to do with how voters choose the president of the USA?

Go on, read the book — I bet you too want to know how Dartnell thinks it did!

— Isabel O'Brien, BSc (Hons) Natural Sciences (Earth Science)

County Clare Field Trip Report, September 2019

Steve Woodward (photographs are by the author unless otherwise designated)

I think I speak for all who attended the 'Father Ted' weekend in County Clare in saying that we were delighted by our three guides: Prof. John Walsh, Prof. Peter Haughton and Prof. John Murray. Their collective breadth and depth of geological knowledge is immense. Thanks also to Susan Pyne, Phyllis Turkington, *et al.* for facilitating the event.

Overview

Apart from the occasional foray inland, our three-day excursion focused primarily on coastal exposures between Diamond Rocks at Kilkee and the Aillwee[1] Cave (Fig. 1). *[Notes on page 103 — Ed.]* A glance at any geological map will show you that Ireland comprises primarily Carboniferous rocks, so this was to be very much a sedimentary weekend, with frequent references to *Father Ted* filming locations and situations.

County Clare is largely Lower and Middle Carboniferous rocks, with classic examples of large-scale sedimentary features associated with cyclic marine and fluvial deposits, and numerous sea-level fluctuations governing its sedimentology and morphology. At that time, most of the County Clare region was a subsiding basin at the mouth of a large, complex river delta system, fed from a rapidly eroding land mass to the south-west, not unlike the present Mississippi delta.

One particular feature examined was the famous karstified Burren limestone sequence, replete with unusually large-scale clints and grikes, and strewn with glacial erratics. There was also evidence of tectonic activity following the closure of the Iapetus Ocean and the Caledonian Orogeny, and later the Variscan Orogeny. In fact, the Iapetus Suture is concealed along course of the River Shannon.

From my perspective as an OUGS Northumbria Branch member I noticed the obvious absences of the Great Limestone and Whin Sill (295Ma), both of which dominate the Carboniferous landscape in north-east England. Also, being fed from a landmass that was at the time south-west of the Pennines, the rocks and pebbles that litter the County Clare coastline are a shade or two lighter than those in north-east England.

Following are descriptions of some of the key observations and features made during the three-day event. Many thanks also to Alan Driscole, Jane Michael, Isabel O'Brien and Mimi Spencer for their advice, field notes and photos.

Day 1: 6 September

Kilkee's Diamond Rocks, Spanish Point and the Cliffs of Moher

Kilkee's Diamond Rocks are so-named because of the white quartz veins that inhabit the fine Namurian mudstones. The region is characterised by several cyclothems[2], some of which are evidently coincident with Milankovitch cycles. The term 'cyclothem' was coined in 1932 by Harold R. Wanless (University of Illinois), who used it to describe the succession of sedimentation associated with coal-bearing formations and sea-level changes. Figure 2 shows Tullig Cyclothem mudstones originally deposited in the rapidly subsiding Claire Basin, now with NE–SW trending faulting, fracturing and veining. Such was the mass of the material entering the basin that the rapid 'descent' gave rise to lateral slippage of the partially lithified sediments, causing listric faults. These features were at first misinterpreted as small-scale graben faults, but closer inspection revealed the characteristic curved fault planes. Parallel to the main veins, smaller, *en échelon* veins were also observed (not photographed), representing a much later Variscan Orogenic influence (N–S compression). Quartz veining is believed to have begun at depth *c.* 20Ma after lithification, when the rock temperature was 250º to 350ºC.

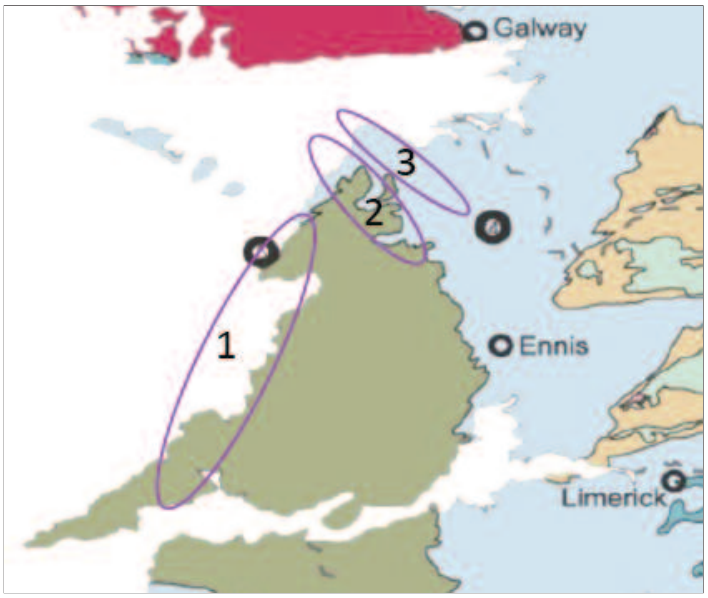


Figure 1 Approximate areas covered by the field trips on days 1, 2 and 3.

Figure 2 Diamond Rocks, so-called due to the quartz veins in mudstone.

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Figure 3 The clear blue waters of the Atlantic Ocean, viewed from Kilkee clifftop (Diamond Rocks), looking north-east across the bay at St George's head strata dipping beneath Kilkee golf course.

Today, there is little sediment in suspension within the coastal waters surrounding the bay, making it possible (with appropriate attire!) to observe the 'bare' geological landscape farther out in the Atlantic Ocean. We were reminded of this fact as we walked along the cliff-top path towards Bishop's Rock, our next location. The breaking waves, a stunning turquoise blue, reflected the clear waters beneath (Fig. 3).

The region has evidence of five cyclothem units related to sea-level change, the three in our locale being the Tullig, Kilkee and Doonlicky. The sea-level changes at that time are thought to have been influenced also by the late Palaeozoic Ice Age.

Milankovitch Cycles

The maximum and minimum peaks in the Earth's orbital eccentricity (distance from the Sun) oscillate over a 100,000yr period; the north–south axis tilt (22.1º to 24.5º) oscillates over 41,000 years; and the axis 'wobbles' (global precession) over a 26,000yr period. These changes in distance and inclination towards or away from the Sun affect the amount of solar energy the Earth receives. Thus, if the Earth is in its closest orbit to the Sun while the poles are simultaneously at maximum tilt, the ice caps increase (although the presence of green-house gases in the atmosphere — man-made, geological or astronomical — have a far greater effect on global temperature).

Farther south along the cliff-top path there is a substantial mud diapir that had risen from the deep. Such features 'arise' due to a combination of hydraulic pressure and inherent buoyancy, i.e. being waterlogged and of lower density than their surroundings (Fig. 4). Like many geological features, these same Earth processes continue today. Mud diapirs[3] are known to occur, for example, in the outer reaches of the Mississippi and Niger delta systems, where rapid deposition imparts an immense hydraulic pressure on the underlying muddy sediments. Mud domes can rise 100m during a 20yr period and may even break the surface to form islands, which, if nothing else, can be a danger to shipping.

Figure 4 The mud diapir exposed in the cliffs at Moore Bay, Diamond Rocks (photo © 2019 Mimi Spencer).

Spanish Point is 30km north of Kilkee, so-named after its Armada legacy. In 1588 many ships of the Spanish fleet were wrecked in a storm. However, any crew members lucky enough to escape their beleaguered vessels were put to death by Sir Turlough O'Brien, the High Sherriff of Clare. The foreshore has a section at the top of the Doonlicky Cyclothem, which here is in contact with the base of Delta Cycle 4, and has horizons dipping *c.* 20º seawards caused by the Variscan Orogeny. One of its more striking features is deeply cut, N-NW-trending basal grooves infilled with sandstone at the contact between the mudstone and sandstone (Fig. 5, *opposite*). These grooves were cut into exposed mud flats by high-energy turbulent currents following the breach of a levée. This is another typical delta system displaying various sea-level changes, and also a period of land exhumation, punctuated with a palaeosol layer containing plant fossils (e.g. Stigmaria) with root bioturbation into the sediment beneath. Desiccation cracks in the mudstone and pyritised fossil bark are also evidence of land exhumation (sea-level drop). Overlying the

Figure 5 Spanish Point Sandstone layer with grooves cut into the silt.

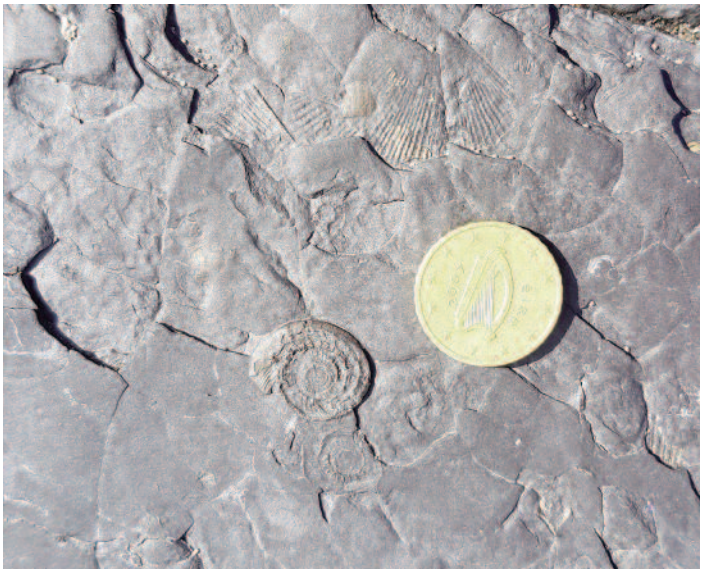


Figure 6 Spanish Point anoxic mudstone harbouring small, pyritised, ammonoid and bivalve fossils.

palaeosol is a highly fossiliferous, black mudstone and with pyritised goniatites ammonoids and bivalves, indicating an anoxic seafloor (Fig. 6). There was some debate about to how these creatures managed to enter what to them would have been a toxic environment. It was recognised, though, that both were 'nektonic' organisms (able to swim unassisted) and as such could have inhabited the higher-level oxygenated waters above.

Our final stop was at the Cliffs of Moher (Fig. 7a), which provide an overview of the whole Clare basin story in one location. Being of mostly of Namurian age, the cliff represents the passage of approximately 13Ma. Looking south, at 200m high the cliffs encompass the Gull Island Formation at their base, ending at the top with the Tullig and the Kilkee cyclothems. The base of the cliffs in this view is the Doolin Limestone (Fig. 7b), which extends seaward to the Aran Islands (Fig. 8).

Figure 8 Aran Islands in the distance.

Figure 7 (a) The cliffs north from O'Brien's Tower (photo © 2019 Isabel O'Brien) (b) Doolin Limestone at the cliff base.

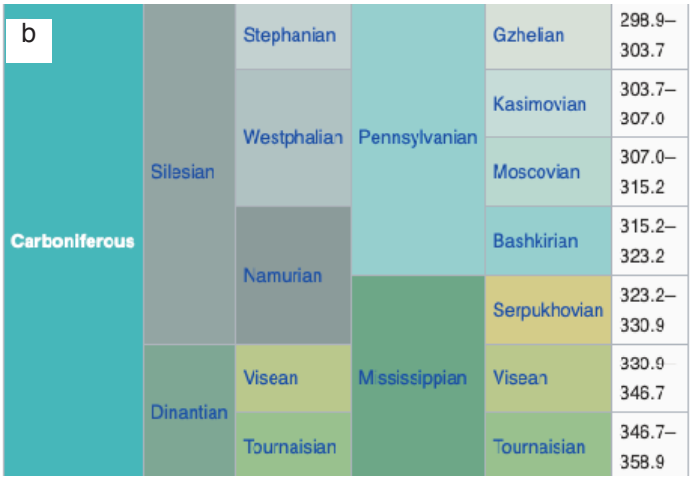


Figure 9 (a) Prof. John Murry explaining the intricacies of Carboniferous nomenclature; (b) old and new subdivisions of the Carboniferous (image source unknown).

Day 2: 7 September

Poulsallagh, Ailladie cliff, the Father Ted's parochial house and St Brendan's Well

On Day 2 we visited Poulsallagh[4] to examine the iconic Burren Formation, a Viséan Carboniferous Limestone sequence *c.* 800m thick. Prof. John Murray first explained to us the new Carboniferous Period nomenclature, harmonised in 2004 and given official colour designations to reflect collaboration between various international geological organisations (Figs 9a and 9b). The Burren landscape is a textbook example of karstification, but on a grand scale, and is host to classic features such as cave systems, underground rivers (phreatic[5]), clints, grikes, kamenitzas (or panholes) and other features (Fig. 10). The surface was rendered barren (superficially at least) by retreating ice

Figure 10 Karstified Burren landscape with clints, grikes and glacial erratics (photo © 2019 Mimi Spencer).

sheets *c.* 14ka — 'superficially' because the grikes are in fact home to about half of all the plant species in Ireland. Numerous glacial erratics also pepper this landscape, some on 'pedestals' and some not, the reason for which was discussed at some length, as was the origin of the surface penetrating kamenitzas. Karstification is a dissolution process in which naturally acidic rain (due to absorption of atmospheric carbon dioxide) dissolves the limestone and preferentially attacks natural fractures and calcium carbonate veins within the limestone. Close inspection of the kamenitzas (Fig. 11), which are actually embryonic clints, shows the process in action: dissolution of a slender interconnecting vein between the three depressions. We are told that the same process, on a grander scale, was instrumental in forming the Aran Islands of Inisheer[6], Inishmaan and Inishmore, as indicated by the large calcite vein on the coast of Inishmaan; and the dissolution continues to affect Inishmore, which might eventually result in it being 'Inishless' (Fig. 12)!

The pedestals supporting some of the erratics are raised prominences of limestone bedrock created by erosion. Not all the erratics are supported on pedestals, which is a mystery in itself, and possibly related to the shape of the erratic? A survey of the pedestals reveals their mean height to be *c.* 280mm, giving us an erosion rate of 1mm per 50 years since the ice sheet retreated (Fig. 13a, *opposite)*. This is possibly a non-linear rate of erosion and likely to have been accelerated since the advent of the industrial revolution. It was remarked that a similar erosional process can occur during a single tidal cycle on mud flats affecting pebbles that were left stranded at low tide (Fig.13b, *opposite*).

For example, Figure 13b shows a shallow-angle beach at Redcar in north England, where the receding tide, possibly exacerbated by torrential rain that day, flows around the stranded pebbles,

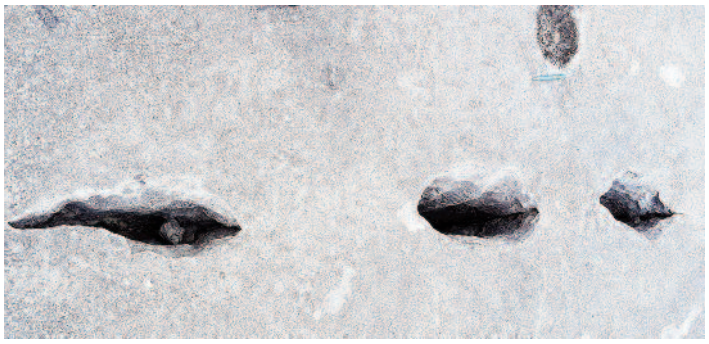


Figure 11 A line of kamenitzas (panholes) joined by a slender calcite vein.

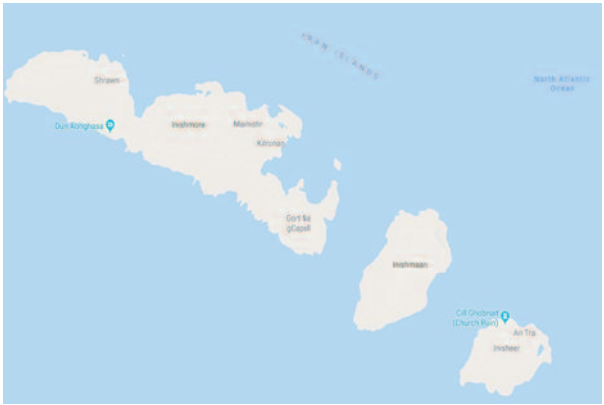


Figure 12 The Aran Islands showing Inishmore (on the left), which is on the way to becoming two separate islands (source: Google Maps).

Figure 13 Comparing long and short-term erosional processes that can be instrumental in the creation of pedestals beneath (a) glacial erratics (photo © 2019 Isabel O'Brien) and (b) pebbles on the beach (Redcar beach — Jurassic ammonite fragment added for scale).

some of which are left 'high and dry' on mud pedestals, but many of which are not. When this seemingly random sculpting of mud pedestals has happened in one tidal event, one might surmise that the Burren erratics are being subjected to similar fluid dynamics over a longer time period.

Another mystery feature of the Burren landscape is the random occurrence of irregular depressions that did not appear to be associated with acidic dissolution. It was suggested that these might be the result of tree root penetrations.

Not all of us completed the hike along the clifftop and steep descent to the beach, but those who made it to the foot of the Ailladie[7] Cliff saw that it is an exposure characterised by massive and relatively featureless sequences with few bedding planes (Fig. 14), suggesting deposition at a rate of *c.* 20mm per 1,000 years. Even more featureless was the adjacent 'Mirror Wall' exposure (just out of sight to the right of Fig. 14), which at the time of our visit was festooned with ropes and climbers, who have renamed the outcrop to 'reflect' its smooth appearance.

Prof. Murray explained that we were in a setting equivalent to the modern-day Bahamas, and that the occasional horizontal discontinuities represented some sort of depositional interruption. Examination of the cliff base beneath the overhang revealed a wider 'interruption' seemingly in-filled with a softer sediment (Figs 15, *below*, and 16, *overleaf*). Closer inspection of this band shows the upper contact with the limestone to be relatively flat, with the lower contact margin exhibiting an undulous topography,

Figure 14 The foot of the Aillaide cliffs, and the mirror wall to the right (photo © 2019 Isabel O'Brien).

Figure 15 Close-up view of Aillaide cliff base beneath the overhang, showing a band of soft sediment (arrowed) (photo © 2019 Jane Michael).

Figure 16 Excavated clay-like sediment (photo © 2019 Isabel O'Brien).

or more correctly, a mamillated surface (covered with rounded protuberances). In fact, the upper surface of the lower limestone sequence is karstified, indicating exposure to atmospheric weathering. There are also rootlet fossils in the upper reaches, further supporting the supposition of exposure to atmosphere for a significant time period.

Figure 16 shows a sample of excavated soft, yellow-brown sediment, which is somewhat surprising as one might normally anticipate such horizons to be black and shale-like. When wetted the sediment took on a clay-like consistency and did not react to dilute hydrochloric acid, so is a non-calcareous material. When freshly exposed this material is sometimes green, but despite all this information, and after several attempts at compositional analysis, its precise origin remains unclear. Finally, certain isotopes within it suggest volcanic influences.

These relatively friable layers within the horizontal discontinuities are termed clay 'wayboards'[8] — they indicate the presence of a regionally extensive palaeosol layer, i.e. not purely an edge effect, and are the reason for the characteristic terracing of the Burren sequence. When the sea level dropped, the carbonate platform was exposed, resulting in the formation of 'hardgrounds' that were subject to karstic weathering below a thin layer of claystone. Local infilling of any depressions created a relatively flat surface onto which the next limestone sequence was deposited. Because the clay wayboards are non-calcareous they present an impermeable barrier to 'modern-day' karstic weathering processes. When descending water meets a clay wayboard it is driven horizontally until it next contacts limestone, whereafter it can dissolve a vertical crevice and convert the once almost monolithic structure into a complex system of subterranean rivers and caves.

The source of the clay in the wayboards has long been a geological conundrum, and the reason for it not having become lithified baffled some of us students.

After a break for tea and scones at *Father Ted*'s parochial house (Fig. 17), we made our way to St Brendan's Well (actually a river bed), where the contact between the top of the Viséan (Burren) carbonate sequence and the overlying Clare Shale Formation is exposed (Fig. 18). This 400mm thick limestone horizon has been designated as part of the Magowna Formation, the upper half of which is phosphate-rich. Similarly, contact with the Clare Formation is punctuated with an even more slender (40–50mm) phosphatised horizon. Normally, such thin beds would barely register as separate entities on a geological map, but in these cases, both represent important delineations in the sequences. The high phosphate content is derived from concentrations of skeletal matter, which is indicative of reduced rates of sedimentary deposition.

Day 3: 8 September

Burren National Park and Aillwee Cave

We began Day 3 at the Burren National Park, where we were joined briefly by geologist Colin Bunce, head of field studies and senior instructor of cave, mountain and orienteering at the Burren Outdoor Education and Training Centre. This location, overlooking a turlough[9] at the foot of Mullaghmore Mountain, had been earmarked for a visitor interpretative centre and car park, but this plan was abandoned owing to local 'unrest'. A centre was eventually built >20km away in the village of Kilfenora.

Here in limestone country – and in contrast to the countryside within the Clare shales, where there is abundant surface water (as observed on the journey from Ennistymon) – surface water occurs only in turloughs, described to us as 'ephemeral lakes', because they 'ebb and flow' with the rise and fall of the underlying water table. Water flow here is subterranean and it has created a complex cave system comprising a series of horizontal and vertical 'conduits' that interconnect subterranean cavities containing

Figure 17 Most of the group gathered outside Father Ted's parochial house (photo © John Pyne).

Figure 18 Limestone horizon, the upper half of which is phosphatised.

Figure 19 (a) Mullaghmore (180m) monocline with terracing and turlough (photo © 2019 Jane Michael); (b) also viewed from the other direction through the parochial house lounge window.

so-called 'perched water'. Prof. Walsh likened them to a plumbing system with multi-level bathtubs. Generally, there is a preferred route through the system as one 'bath' fills up and overflows into the next one and so on. Every now and then, however, a freak storm results in the water course not being able to accommodate the deluge, which forces the water to take the next path of least resistance in an unpredictable manner, which can cause flooding. Such freak storms used to be a once-a-century event, but with the advent of global warming the frequency of flash flooding of the cave system is dramatically increasing.

The area has been glaciated into terraces with horizontal divisions coinciding with the clay wayboards, which have created a series of spring-lines where there is a step change in topography. Faults are not immediately obvious, but the high ground here — e.g. Mullaghmore (*Mullach Mór*, 'Great Summit') — is actually a monocline fold up against a fault, with asymmetric folds moving in a southerly direction and downthrown to the south, forming a basin (Fig. 19). Some of the valleys are also monoclines. The fold axis is NE–SW, which is the same orientation as the quartz veins seen on Day 1, and related to Variscan compression and hydraulic fracturing.

The weather deteriorated on this final day, so we were pleased that our next stop was the Aillwee Cave, where we witnessed first-hand the subterranean effects of long-term limestone dissolution. The cave was discovered in 1944 when Jack McGann's dog chased a rabbit behind a bush, revealing the previously unknown entrance. Oddly enough, Mr McGann kept his secret until 1973, when he happened upon a group of cavers in the local pub. The cave was opened to the public in 1976. 'Marine Blast' tunnel (250m long) was completed in 1992 to create a circular route. Exiting at the man-made tunnel we again encountered an extensive clay wayboard at about knee height, confirming the widespread subterranean extent of the palaeosol layer. Our guide was more than a little perturbed by having to deliver his presentation to a group of geologists, and nervously began to explain the origins of the keyhole-shaped profile of the phreatic tube in the cave roof. He might have been less nervous had he known that many in the group had learned of phreatic tubes only two days previously!

The cave system comprises *c.* 1km of tunnels within the heart of the limestone hillside. However, only about a third of the complex is accessible to the public. At the entrance we were greeted by the remains of a long-dead (now extinct) brown bear, the bones of which have been dated as 10,400 years old. There were actually two sets of bones found, but the second set was considerably younger at 4,600 years old. Aillwee Cave is significantly older than most of the other caves in County Clare and originally contained a large glacial meltwater stream — evident by the phreatic tube high up in the cave roof. The stalactite and stalagmite formations in the main cave are no more than 8,000 years old, but some of the calcite straws in the cave recesses may be 35,000 years old. It's a matter of luck whether dripping water forms a stalactite or a hollow straw, but if a straw is formed it rarely grows longer than 300mm due to its inherent fragility. Selected calcite formations have been subject to various forms of analyses, which are providing useful post-glacial climatic data.

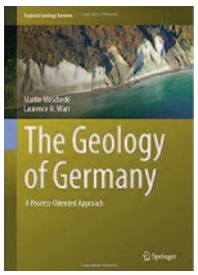
Finally, a couple of extra images show John Walsh accepting his 'golden leader' award for services rendered (based on *Father Ted*'s 'golden cleric' award) (Fig. 20).

Figure 20 Prof. John Walsh receiving his 'golden leader' award, a reference to the Father Ted *TV series (photo © 2019 Isabel O'Brien).*

Notes

[1] very dark caves, almost like being blind!
[2] from the Greek *thema* meaning 'laid down' (laid down in cycles)
[3] from the Greek *diapeirein* meaning to 'pierce through'
[4] a term that can variously mean 'dirty hole' or 'polluted cave'
[5] below the water table, whereas vadose waters inhabit a region below ground but above the water table
[6] Inisheer (a.k.a. Craggy Island) was the island selected for the opening sequence of the *Father Ted* TV series, although it was not used otherwise in the series; and the parochial house is, in fact, on the mainland.
[7] an abbreviation of *Aill an Daill*, meaning 'The Blind Man's Cliff'
[8] a term first coined in Derbyshire
[9] from *Tur lach*, meaning 'dry place'

Book Review



Meschede, Martin, and Warr, Laurence N. 2019 *The Geology of Germany, a Process-Oriented Approach*. Springer Nature Switzerland (ISBN 978-3-319-76101-5; 304pp; ISBN 978-3-319-76101-5; hardback £69.99; ePub ISBN 978-3-319-76102-2; €67.40)

This book is part of Springer's 'Geology of … Series'. The series aims to present a state-of-the-art overview of the geology of a particular country, region or continent, providing a basis of understanding for students, researchers and professional geologists when beginning investigations in a particular area.

The book opens with several brief chapters summarising basic concepts in geology — geological time, rocks and the geological record, and plate tectonics. Although basic, these chapters will serve as a useful refresher for readers who may be less familiar with some of the concepts explored later in the book. Next is a brief overview of the specific plate tectonic history of Europe, placing Germany and surrounding areas in the proper context, followed by an overview of modern seismic activity.

The bulk of the book then covers the geological history of Germany and surrounding areas (at times extending into Great Britain) from the Proterozoic until the Pleistocene. Always placed in plate tectonic context, both sedimentary and crystalline rock formations are described in quite some detail. The two main orogenic episodes, Variscan and Alpine, are discussed in detail. The book ends with dedicated chapters on asteroid impacts and the Pleistocene glaciations.

An Appendix showing a much reduced image of the 1:1,000,000 geological map of Germany with the geological time scale, extensive References, and an Index complete the book.

The hardcover book is lavishly illustrated throughout, with maps, sections, geological columns, block diagrams and many photographs of outcrops, fossils and specimens. Especially useful for a historic understanding are the detailed 'snapshot' maps of the paleogeographical situation at various points in time, with the plate tectonic setting indicated. These maps cover a much wider area than Germany alone and include the UK. In addition to the illustrations there are 26 'breakout boxes' interspersed throughout the text, each covering a specific aspect or geological process in more detail.

Overall this is a very high-quality production. Anyone with even just a minimum of geological background who wants to understand more about the geology of Germany, and of central and north-west Europe in general, will find this volume invaluable. For anyone contemplating a geology field trip to Germany, this book is a 'must'. Highly recommended.

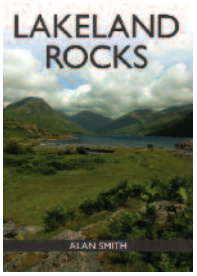
An ePub version is also available, but with so many illustrations throughout the text this may be a bit harder to navigate and read.

Full-size copies of the geological map of Germany can be ordered at https://www.bgr.bund.de/DE/Themen/Sammlungen-Grundlagen/GG_geol_Info/Karten/Deutschland/GK1000/gk1000_inhalt.html

More information about the series can be found at http://www.springer.com/series/8643.

— Jur Snijder, MSc Geology (U Amsterdam)

Book review



Smith, Alan 2019 *Lakeland Rocks.* Ramsbury, Marlborogh, Wiltshire: The Crowood Press (ISBN 978-1-78500-651-7; 160pp; paperback £16.99)

Books and booklets about the English Lakeland's geology and landscapes have been proliferating for decades. They sell well to a dedicated group of local geologists and to an army of fell walkers and climbers. My own introduction to studying and understanding Lakeland rocks began with E. H. Shackleton's *Lakeland Geology: Where to Go: What to See* (Dalesman 1973, for just 90p!; first edition 1966).

Alan Smith himself has contributed to this specialised flow in, for example, his *The Ice Age in the Lake District* (Riggs Side Publications 2008) and other booklets.

Dr Smith's new book on Lakeland rocks is not a tour de force, but rather a tasting, a brief and readable guide to the main types of stone in the Lake District and where to see them; a book that can be read and enjoyed when walking the fells and when sitting back at the fireplace. The nice thing about the Lake District is that it is so compact — I once circuited it over three days with two overnight stops, weaving my way through its passes and along its ridges with Shackleton in hand.

With Alan Smith's new book you can also do this. Although not as detailed as the two volumes of individual chapter-articles, *Lakeland Rocks and Landscapes: a Field Guide* (1992) and *Exploring Lakeland Rocks and Landscapes* (2008) both published by the Cumberland Geological Society, Dr Smith's guide gives you plenty of solid, digestible information, briefly, and includes nearly 100 photographs of what you are meant to see. His text tells you the basic geological background of the Lake District, then takes you around it in words on and photographs of the rocks in somewhat eclectic-entitled chapters: 'Skiddaw rocks', 'Volcanic rocks', 'Silurian sedimentary rocks', 'Granites', 'Dyke rocks', 'Sills', 'Minor intrusions', 'Basic igneous rocks', 'Metamorphic rocks', 'Carboniferous rocks', 'Conglomerates and breccias', 'Permian and Triassic rocks', and 'Clay'. Two appendices provide a 'Classification scheme for igneous rocks' and a 'Scheme for describing sedimentary rocks'. The book ends with a Glossary, a guide on where to find out more and an Index.

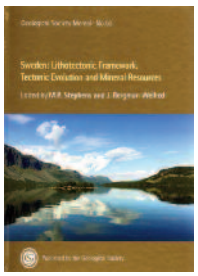
This is a 'fun' book; what I think would be said in Spanish: *sabroso*. As well as explaining the rocks, it touches on how they were, and are, used in the Lake District; how the rocks have shaped the landscape and something about how they have affected the lives of those who live there. My favourite photographs are of the famous 'Musical Stones', a xylophone of Skiddaw slate bars (in the Keswick Museum); and the 'Ruskin Rocks', a new rock xylophone of machine-cut rock bars, the product, no less, of an interdisciplinary research project at the University of Leeds, now displayed in Brantwood, Ruskin's house in Coniston — both ancient/modern rock bands.

If you have no books on Lakeland rocks and want a short, easy–to-read, informative book about Lakeland stone, this is the book for you. For one who has several such books already, I am equally pleased to own this one.

— Dr David M. Jones, OUGS Proceedings Editor

Book review

Stephens, M. B., and Weihed, J. Bergman (eds) 2020 *Sweden: Lithotectonic framework, tectonic evolution and mineral resources*. London: Geol Soc Mem 50 (ISBN 978-1-78620-460-8; 631pp; hardback £140; GS Fellows £70)



I am lucky to have an abandoned granite quarry (1.4Ga) in the garden of my house in Sweden! This granite was emplaced into metamorphosed volcanoclastic sediments and gneisses (1.7–1.8Ga). Mapping the granite and host rock is relatively straightforward, as is identifying structural features, but understanding the regional setting remained a dark and unknown art to me until now.

Geological Society Memoir 50 is edited by former Swedish Geological Survey (SGU) geologists and pulls together decades of work by the SGU and a number of leading Swedish universities. The current lithotectonic framework was 'established' in 2012 with the publication of the 1:1 million geological map of Sweden.

I was in two minds about offering to review yet another GSL publication — my experience has been disappointing, with the GSL pursuing what seems a 'never mind the quality, feel the thickness' approach to its publications. However, this memoir is excellent, and exceeded my expectations — the editors and authors are to be congratulated.

The editors have organised the memoir 'stratigraphically' into eight parts, with the first five describing orogenies over the period 2.0–0.9Ga (located to the east and south-west). The remaining three sections relate to the Neoproterozoic stratigraphy, Caledonian Orogeny and post-Caledonian geology. These eight orogenic events account for the 2.5 billion year accretion of the Fennoscandian Craton.

As an example, Part V — the Sveconorwegian Orogeny — is split into four chapters. The first chapter tees up the regional and lithotectonic framework. The Eastern Segment — comprising descriptions of orogen boundaries, ductile shear and mylonite zones — makes up the second chapter. The third describes polyphase deformation and metamorphism history of the western Idefjorden Terrane. The final chapter pulls together the geological history and orogenesis.

Each orogen and its sub-component terranes are described systematically and cover: the nature of the orogen boundaries; the lithology; deformation schemes and processes; radiometric ages; geochemical characteristics of the key stratigraphic rock lithologies; and mineralisation. This approach enables the reader to understand the tectonic setting for each orogeny and the temporal interaction between orogenies.

I particularly liked the authors' recognition of uncertainty — each chapter has a section entitled 'Key issues needing future work'. I suspect this is also a very Swedish way of dealing with a number of controversies!

Mineral exploration and production has a long history in Sweden and the country's continued importance is recognised, particularly by the EU, as a source of critical and strategic minerals. Mineral deposits are explained in terms of the lithotectonic framework, giving the reader an understanding of the 'local' controls set in a regional picture. Careful reading by interested explorers reveals much — such as the discovery in 2017 of diamonds within the Caledonian Orogeny.

I have some criticisms. Firstly, there are many cross-references to papers within the memoir and at times this feels a bit circular and really annoying, but probably necessary (see Part V above) to explain the interaction between each terrane. Secondly, given the complexity of the Proterozoic tectonic history there is a dearth of cross-sections and 3D models to explain the ideas developed. I counted *only* 12 cross-sections (excluding deep seismic profiles), and eight of those relate to Sveconorwegian Orogeny. Finally, the editing could have been more concise in places — long sentences do not necessarily make explanations more valid!

The memoir is a valuable resource for professional geologists and academics studying complex geological areas and essential for anyone studying Swedish geology. The authors (and the SGU) have come up with an effective approach to synthesising and deconvolving complex cratonic geology and will stimulate anyone to find out more about geological processes in the Proterozoic!

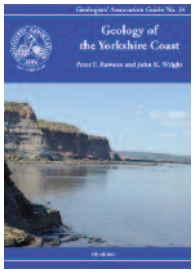
• Data from the memoir are available at https://www.geolsoc.org.uk/Publications/Books/Memoirs/Memoir50data

• SGU data is freely available and has an easily accessible electronic and GIS database (in Swedish and English) https://sgu.se/produkter/geologiska-data/

— Stephen Crabtree

Book review

Rawson, Peter F., and Wright, John K. 2018 *The Geology of the Yorkshire Coast* (4th edn). London: Geologists' Association Guide No. 34 (ISBN 978-0900717-95-6; 178pp; spiral bound £12.00)



This book in the popular 'GA Guides' series is the fourth edition of a guide to the geology of the Yorkshire coast. This new book is a revised edition of the earlier GA guide to the Yorkshire coast expanded with the addition of material from the earlier and now out-of-print GA guide to Hull and surrounding areas. This present guide covers the Yorkshire coastal exposures comprehensively from Runswick Bay in the north, down to the Holderness coast in the south of the area.

The format of the book follows the standard GA Guide A5 size, and is spiral bound, which makes it very convenient for use in the field. The text is amply supported by well laid out and helpful maps and diagrams and is easy to use. It is printed on paper that looks as if it could withstand a brief shower, so overall it is ideal for taking out in the field.

The guide begins with an introduction to the geology of the area covered before detailing individual itineraries, which are discussed from north to south. There is a comprehensive bibliography at the end of the book. References are updated from the previous edition to include the results of new and current research on the area.

The final part of the introduction briefly documents the extensive industrial history of the region. Building stone extraction and coal working predated the alum industry, the latter working the Alum Shales on a major scale, leaving behind much evidence in the present landscape. Even more impact on the landscape resulted from extensive working for ironstone from the early 1800s, and the remains of pits and former adits abound along the coast. Potash mining, from the mid-1960s onwards, has been kinder on the landscape, with extraction taking place deep underground. This section helps to explain much of the very evident surface features visible across the area today.

Chapter two has a welcome inclusion of seismic data from UKOGL, the seismic on-shore library database, and from the commercial data sets of Sirius Minerals, who have interests in the exploitation of underlying polyhalite resources in the area. This inclusion helps to illustrate the underlying structure of the region, and its complexity. The Robin Hood's Bay dome and the graben-structure of the Peak Trough and Peak Fault are given detailed coverage. The Flamborough Fault Zone, an area of intense complexity, is also appropriately covered and illustrated by seismic section detail.

The guide comprises 17 excursion itineraries effectively covering the coastal sections from The Tees to The Humber. Some inland sections are also included, notably the eastern side of the North York Moors from Egton Bridge to Grosmont (Itinerary 7), and the Betton Farm Quarries SSSI exposures at East Ayton (Itinerary 10). The classic coastal sections of Robin Hood's Bay, Whitby, Staithes, Filey and Flamborough are all covered in appropriate detail. The critical Quaternary sections of the southern Holderness coast are also well documented and covered comprehensively. The classic Dimlington type-section of the Dimlington Stadial, the most significant evidence of the last Devensian glaciation in eastern England, is also accorded due coverage (Itinerary 17).

My only gripe with this otherwise excellent book, and mainly a personal one, is in the historic use of the term 'sequence' when describing a series of strata rather than the term 'succession'. In sequence stratigraphy the term 'sequence' has a particular meaning, which is not implied in the descriptions of the stratigraphic sections detailed here.

Overall this is a very worthy successor to the previous edition and should find a place on the bookshelf of anyone interested in the geology of eastern England.

— Paul F. V. Williams

Book review

Duffin, C. J., Gardner-Thorpe, C., and Moody, R. T. J. (eds) 2017 *Geology and Medicine: Historical Connections*. London: Geological Society (ISBN 978-1-78620-283-3; 290pp; £100 from Geol. Soc., £105 elsewhere)

The book was produced by the History of Geology Group of the Geological Society following two conferences on the subject. It is a collection of papers, reviews and biographies by various authors and as such, each chapter has a different writing style.

It starts with an overview of physicians, apothecaries, geologists and geology through the ages and civilisations that have helped form our present-day knowledge. It follows with the historical records and biographies of significant physicians who either used geology in their work or contributed to the advancement of Earth science as a hobby, including Dr Otto Sperling, William Hunter, James Parkinson (of Parkinson's disease fame), Dr Pau Estorch Siques, a host of Italian physicians and others.

Much of the historical connection with doctors revolves around the use of clean and mineral water supplies. The book details the work of Nathaniel Hodges — the plague doctor — and his use of purging wells. It describes the efforts made to supply Milan with clean water, which has helped make it the city it is today.

The second section of the book is dedicated to the use of earths, minerals and metals in medicine. This includes the chemotherapy and the antibacterial properties of some clays. A serious omission in my view, since I trained as a radiographer, is a better history of radioactivity in medicine, although it does detail the early application of X-rays to palaeontology.

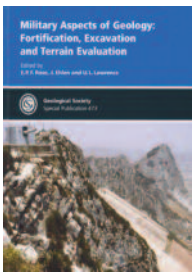
The final chapters deal with such delights as serpent stones and medicinal unicorn horn — a fascinating horrible history of mythical medicinal cures. Many of these can be linked to fossils that we readily identify today, including snakestones masquerading as ammonites, and unicorn horn seemingly the collective noun for various fossilised ivories such as mammoth teeth and tusks, and narwhal tusks. There are chapters on the medicinal use of precious, semi-precious and coral stones in the 16th and 17th centuries. The concluding chapter deals with toxic earth minerals and metals such as lead.

I found this book fascinating. It is well referenced, as you would expect from the Geological Society. It makes an excellent starting point for any research on the subject. Each chapter stands alone very well, so although some chapters are quite technical, the book is easy to dip into for information. The medical content is aimed at geologists, so a lay knowledge is enough to enjoy this good read.

— Sally Southall, BSc Natural Science (Earth Science) (Open), Dip. College of Radiographers

The Editor would like to apologise to Sally Southall. Her worthy review of Geology and Medicine: Historical Connections *was, in fact, delivered well in time for last year's* OUGS Proceedings *but was unfortunately misplaced in the scramble to prepare the issue for the printer, and thus left out. The book is an interesting application of geology and Sally is the ideal OUGS Member to write this review of it. I am pleased that the unintentional omission was detected and that I have now been able to rectify my error!*

Book review



Rose, E. P. F., Ehlen, J., and Lawrence, U. L. 2019 *Military Aspects of Geology: Fortification, Excavation and Terrain Evaluation.* Geol Soc Spec Publ 473 (ISBN 978-1-78620-394-6; 314pp; hardback, £110)

This book is wide ranging and eclectic, and after an introductory paper is split into three sections. The earliest is the Roman fort at Lympne in Kent. However, most of the papers cover aspects of both World Wars, in all theatres and end with Islamic State military tunnels in northern Iraq.

The introductory chapter describes the overall history of military geology. Napoleon was the first to include geologists in a military operation. In Britain and Ireland, geological mapping started under the auspices of the army, and only became a civilian government agency in 1845, as the Geological Survey of Great Britain. The introduction finishes with brief outlines of the careers of notable military geologists.

The remainder of the book is divided into three sections: 'Coastal Fortification', 'Excavation' and 'Terrain Evaluation'. 'Coastal Fortification' covers the late 3rd-century Roman fort at Lympne, its principal interest being the accurate dating and magnitude of the movements. Further papers describe groundwater supplies to Victorian forts, American coastal defence forts in the American Civil War and, finally, the German WWII defence engineering geology in Norway.

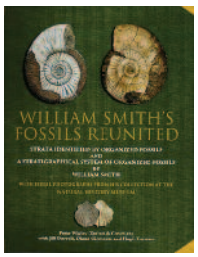
'Excavation' is the longest section. It commences with a comprehensive paper on WWI trench construction; then describes German military geology and mining on the Eastern Front in WWI; then has three papers by Rose on the Royal Engineers' quarrying and tunnelling works in both World Wars. Interestingly, in WWI there was a big emphasis on locating quarries for stone to supply the trenches and front-line areas, whereas in WWII the British moved from defensive construction after Dunkirk to planning for D Day and the construction of military infrastructure in all theatres of WWII. The final two papers are on British tunnels in Hong Kong and in the Islamic State in Northern Iraq. In Iraq, this work included significant underground infrastructure, for which specialised tunnelling machines were made.

The final section on 'Terrain Evaluation' includes papers on the Red River Campaign in the American Civil War, on aerial photographic intelligence in WWII and the role of significant British geologists in these operations, and finally a review of a century of German cross-country mobility prediction. British geologists who analysed the aerial photography included D. L. Linton (for attacks on the Tirpitz and V-weapon storage sites — later a geographer who worked on the on the Weald), and P. Allen (who "seems to have worked around the clock" carrying out his geological field work during the days when on night shifts, and when on days carrying out research at night!).

Well worth a read, covering a wealth of material — as was, and is, the approach of different governments to military geologists. The British had handfuls, the Germans hundreds and the Russians thousands.

— John Lonergan, FGS, BSc (Hons) Geology (Open)

Book review



Wigley, Peter (ed and comp), Darrell, Jill, Clements, Diana, and Torrens, Hugh 2018 *William Smith's Fossils Reunited: Strata Identified by Organised Fossils and a Stratigraphical System of Organised Fossils by William Smith with Fossil Photographs from his Collection at the Natural History Museum*. Halsgrove: Natural History Museum and The Geological Society (ISBN 978-0-85704-337-5; 150pp; hardback £34.99)

Published by the Natural History Museum and the Geological Society, the extended title of *William Smith's Fossils Reunited* fully describes its scope and purpose. This is not a biography of William Smith, but rather an enhanced collation of two of William Smith's key publications, with significant additional material to give depth and context.

This book incorporates two of William Smith's publications: *Strata Identified by Organised Fossils* and *A Stratigraphical System of Organised Fossils with reference to the specimens of the Original Geological Collection in the British Museum*. Both of these works were published soon after Smith's 'Great Map' (1815) and at a time when Smith was undergoing financial difficulties. *Strata Identified by Organised Fossils* (1816) was planned to be a series of seven volumes, of which only four were published, describing 34 stratigraphic units with engravings of the characteristic fossils by Smith's collaborator, the illustrator James Sowerby. *A Stratigraphical System of Organised Fossil*s (1817), also unfinished, was a detailed catalogue of the fossils described in the earlier publication, which form part of the fossil collection that Smith had sold to the British Museum in 1816.

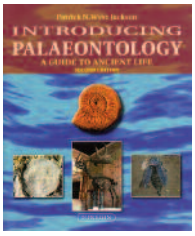
A large part of the appeal of *William Smith's Fossils Reunited* is the presentation of the text of Smith's publications and the juxtaposition of Sowerby's original engravings with newly commissioned photographs of the corresponding fossils from Smith's collection at the Natural History Museum. The book is enhanced by informative introductions to each of Smith's publications, and an account of Smith's sale of fossils to the British Museum. Further related works by Smith are incorporated, including his 'Geological Table of British Organised Fossils', 'Stratigraphic Table of Echini' and 'Table of the Distribution of Ammonites'.

Unpublished gaps in Smith's works are represented by his sketches and notes, and by new photographs. The final chapter of the book presents several handsome reproductions of various parts of Smith's map, each showing where he collected many of the index fossils (his original map did not include this information).

An initial impression of a sumptuous coffee table book belies a thoroughly researched and scholarly treatise that both explains the provenance and expertly presents the component text, plates and photographs to deliver a comprehensive account of Smith's published works on strata and index fossils, with memorable layout and illustrations. The overall quality of the book is heralded by Sir David Attenborough's Foreword, which gives an excellent précis of the content and purpose of the book with an emphatic endorsement of the importance of William Smith's contribution to geology in general and stratigraphy in particular.

— Dominic Davey, BSc (Hons) Geology (U Wales)

Book review



Wyse Jackson, Patrick N. 2019 *Introducing Palaeontology: a Guide to Ancient Life* (2nd edn). Edinburgh: Dunedin (ISBN 978-1-78046-083-3; ix +135pp; paperback £9.99; also as PDF 978-1-78046-622-4, ePub 978-1-78046-620-0 and Kindle 978-1-78046-621-7)

The first edition of this popular introduction to the science of palaeontology was published in 2010. During the intervening nine years there have been many new fossil finds, new interpretations and new techniques developed for studying fossil finds.

Patrick Wyse Jackson's original book was a welcome, brief, but thorough introduction to what is a fascinating hobby, as well as a serious scientific pursuit, to many. The first edition filled a gap in providing a solid text aimed at the 'general reader'. This second edition is equally welcome as a well considered update of the original text.

The text has been revised to address comments on the first edition, especially to include new evidence on the earliest life on Earth, on the development of the molecular timescale, on using computer modelling to create virtual fossil images, and on research discovering the real life colours of fossil plants and animals. The time scales have been updated according to the 2018 International Chronostratigraphic Chart.

Introducing Palaeontology is just that: a taste of a vast field of study encompassing more than four billion years; a guide into the science.

The book is divided into two parts. The first part describes the science of palaeontology, briefly describing its history and development; the basics of fossilisation; fossil collecting — including the all-important 'Code of conduct' for collectors; the use of fossils to interpret and to reconstruct ancient life and environments; and a section on colour in fossils.

The second part comprises 18 subsections, each devoted to a major fossil group: algae and vascular plants, unicellular animals, sponges, cnidaria, bryozoans, molluscs, brachiopods, echinoderms, arthropods, graptolites, conodonts, fishes, tetrapods and amphibians, reptiles, birds, mammals, and finally hominids and hominins; and finishing with a section about trace fossils.

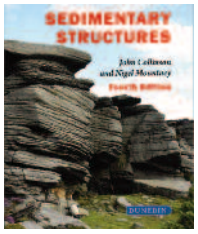
The book has more than 100 good-quality illustrations, in colour throughout; and is enhanced with many excellent fossil drawings by John Murray.

There is no index, but a useful Glossary provides a quick reference to all the terms emboldened in the text when first mentioned.

Commendably, Wyse Jackson includes a reading list at the *beginning* of his book. His introduction is meant to entice into you and lead into the world of palaeontology and fossil study, as well as to fossil collecting. He helps you discover where to find out more, which, in my opinion, the book will 'make you want to'. It is reasonably priced and would make a great gift —not only for yourself, but to friends and relations of any age interested in the study of ancient life.

— Dr David M. Jones, OUGS Proceedings Editor

Book review



Collinson, John, and Mountjoy, Nigel 2019 *Sedimentary Structures* (4th edn). Edinburgh: Dunedin (ISBN 978-1-78046-062-8; xii +340pp; paperback £35; also ePub 978-1-78046-602-6 and Kindle 978-1-78046-603-3)

Professors John Collinson and Nigel Mountjoy's fourth edition of *Sedimentary Structures* is decidedly a textbook, both by intention and declaration. It has a solid, detailed text (no pun intended) meant for frequent and repeated reading and consultation.

This is a textbook worthy of the definition. The book's back-cover notes declare that the book will "appeal" to several categories of reader. These notes' author, mercifully, does not actually use the phrase 'a wide range of', as do so many book blurbs these days, but does list so many groups that 'a wide range' is clearly implied. (Let it be put on record that I dislike the phrase 'a wide range'. It seems that these days *everyone* uses it for *everything*. It is usually not so and shouldn't be: different books are written for different groups of readers. Novels are for a wide readership. Textbooks and scientific books in general are written for different levels and experience of readers. If you dive into a book too advanced for your knowledge, you will only find yourself frustrated and having to dive back into the books used by the authors, to gain the understanding to read his/her book afterwards.)

This is a student text. It is, in fact, declared as such: "…[it] is designed principally for use in undergraduate settings…".

Well, maybe.

The detail in this book is magnificent, even though the authors occasionally state that a certain topic is only mentioned, because the scope of the book cannot be exhaustive about that subject matter. Nevertheless, I defy finding most post-graduate students with all the detail in this book fully embedded in their brains, leave alone undergraduates. I would say that it is a text for life-long students of any age or educational level who want to understand sediments, how they are formed, how they are altered, and how to use them to reconstruct past environmental regimes and compare how ancient and present-day environments and regimes have changed.

This fourth edition is a significant re-write and update. (The original first edition was published in 1982, and this edition is dedicated to Prof. David Thompson, one of the original authors.) The back cover also states that the book "…is characterized by an abundance of informative illustrations and photographic examples, and introduces colour figures for the first time."

Does it ever! As well as its text there are 339 figures! Chapters 6 and 9 have 101 and 80 figures, respectively!

The figures almost overwhelm the text. In places there are so few lines of core text — sometimes at the bottom or corner of a page (itself festooned with several figures), or after a full page or more of figures — that you have to hunt it down. Often, a single 'figure' comprises several photographs or diagrams. Altogether, I estimate that there are c. 500 illustrations in this book!

This detailed information about the illustrations is by no means meant as criticism. The captions to many figures are longer than the adjacent core text on the page. And that is their strength, for as much can be learned from the captions as from the core text. The core text describes the general principles, depositional regimes, fabrics, structures and post-depositional processes, while the captions provide detailed explanations of examples.

I was pleased to see illustrations of sedimentary structures and forms in places I know myself. Yes! In Namibia I pondered over 'desiccation cracks' at Soussusvlei — evaporated ephemeral 'pans', 'aeolian eroded'. I climbed Soussusvlei's famous massive red sand dunes, and even caused numerous, pleasing little 'grain flow tongues' (Fig. 6.90) as I descended the side of one for a quicker, more adventurous route back to the Land Rover, including an encounter with a grazing oryx at the base of the dune! (He said 'hello' and I made 'a wide range' around him.)

Sedimentary Structures has 10 chapters and six appendices. After an 'Introduction to the study of sedimentary structures' describing the nature of the book, its intent and a general description of the range of sedimentary structures, there follow nine chapters, each dedicated to a specific area of study.

Each chapter has several levels of subsections to confine subject matter to specific topics and to help the reader later to locate areas for reference to some work or sedimentary structure she or he has seen in the field — for this book is not just armchair reading, but compels you to get out there and look at the multitude of sediments around you. (While reading the book, I found that I was 'privileged' to live not only with the River Wey behind my back garden, but also with a flood plain, water meadows and several subsidiary streams; *and* with the delights of February 2020 Jet Stream-influenced Atlantic storms, to provide me with lots of ripples, sets, erosion, gravel banks … to observe, sketch, photograph and then to sit back at home in the evening comparing my observations to the figures in this book. No, we were not flooded; we have water meadows in Godalming for that purpose!)

Throughout the book, there are frequent back and forward references to other chapters and subsections of the book. Such cross-referencing emphasises the interwoven nature of sediments, their deposition and erosion, and the fact that different depositional regimes and fluids can create similar structures, especially when observed in the rock records. This point is particularly relevant to the final chapter, which covers past environmental interpretation. Chapter 9 is a welcome one on the palaeontological evidence so useful in reconstructing ancient environment and on how critters and plants can affect the sedimentary record.

The chapters are:

1 Introduction to the study of sedimentary structures
2 Bedding
3 Basic properties of fluids, flows and sediment
4 Erosional structures
5 Depositional structures in muds, mudstones and shales
6 Depositional structures of sands and sandstones
7 Depositional structures in gravels, conglomerates and breccias
8 Depositional structures of chemical and biological origin
9 Structures due to deformation and disturbance
10 Assemblages of structures and environmental interpretation

The six appendices are dedicated to techniques of study. They include collection, display, analysis and interpretation; sampling and preservation; methods of studying present-day environments; study of trace fossils; sedimentary logging; and an especially useful key to common sedimentary lithologies and structures. These appendices include sample recording and logging sheets.

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Each chapter ends with a section called 'Study techniques', with subsections on field experience in present-day environments and on ancient environments; in laboratory experience and experiments, often including suggestions for modelling; and a 'recommended references' list.

Throughout, as this *is* a textbook, key terms are emboldened at their first usage.

Following the appendices there is a 14-page Bibliography, then a detailed, 20-page Index. Readers will have no trouble finding more to read, or to again locate information within the book.

I only have two critical comments about *Sedimentary Structures*. First, there are some lapses in editorial attention — places where the wording must have been changed at some point and stray words from the original text have not been deleted, making for some odd sentences. Second, although the design of the book is beautiful in general — I've already dwelt upon its wealth of illustration — there are textural design lapses as well, with widowed words and letters in some of the core text and in many of the captions. I found at least one case where it appears that the figure cited must have been renumbered when additional illustrations had been added, and the text citation not changed.

Dunedin Academic Press, which took over the publication of this textbook from the original Terra Publishing, is to be congratulated for publishing this edition and providing sedimentary geologists with an extremely useful practical and reference book.

If you like sedimentary geology, collect this book and deposit it in your library, then use it for years as your post-graduate, post-depositional reference book!

— Dr David M. Jones, OUGS Proceedings Editor

Book review

Le Heron, D. P., Hogan, K. A., Phillips, E. R., Huuse, M., Busfield, M. E., and Graham, A. G. C. (eds) 2019 *Glaciated Margins: the Sedimentary and Geophysical Archive*. London: Geological Society, Geol Soc Spec Publ 475. (ISBN 978-1-78620-397-7; 288pp; hardback £100.00)

This is a well presented book consisting of a dozen research papers on the sediments created by glaciations from the Cryogenian to the modern day, from the Antarctic to the Arctic and places in between. This book builds on previous publications on this subject and, as the title indicates, adds to the sedimentary and geophysical archive. There is a short Introduction, which mentions this previous work and sets the scene for the papers that follow. I would recommend that you read the Introduction, as this will give you a 'feel' for the subject and the order in which you might like to read the papers.

This is a readable book for those with a reasonable knowledge of geology — a novice might need to refer to a geological dictionary (or Google!) for some of the more technical words, but should not be put off by this. Glaciation is a very practical area of research, reflected in the excellent diagrams, maps, photographs, and the odd graph or two, which help to draw the reader in. There are few chemical or mathematical formulae to interrupt the flow of the text. The text is very descriptive and sets out the features, stratigraphy and bedforms to be found within the sediments; in many cases arguing why these are glaciogenic as opposed to any other geological process — apparently it can be difficult to distinguish glacial sediments without examining them very closely indeed.

Where they are recognised, the sediments of the glacial margins have relevance for environmentalists for interpreting past cycles of glaciation, deglaciation and climate change; the hydrocarbon industry for their reservoir potential (particularly in the Middle East); and other geologists interested in the geomorphology and landforms created by glaciers. These are but a few of the reasons for the research and why you might be tempted to read this book.

After reading this book you may still not be able to recognise glacial margin sediments, but will have an appreciation of the difficulties faced by the researchers. I found the paper on the Falkland Islands particularly fascinating; others may find the papers on Antarctica or on the Middle East to be their subject of choice. If you are firmly in the igneous geology camp then maybe this book is not for you, although glaciers do not discriminate in which type of rock they grind up or carry away to a new location!

This book gives a good overview of the sort of research being carried out in this field and the only drawback I can see to owning this book is the price.

— Linda Morley, BSc (Hons) Natural Sciences with Earth Sciences (Open), MSc (Merit) Earth Sciences (Open)

Book review

Peron-Pinvidic, G., Hopper, J. R., Stoker, M. S, Gaina, C., Doornenbal, J. C., Funck, T., and Arting, U. E. (Eds) *The NE Atlantic Region — A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution — an Introduction to the NAG-TEC Project.* London: Geol Soc Spec Publ 447 (ISBN 978-1-78620-27-9; 467pp; hardback £120)

The Northeast Atlantic Geoscience (NAG) Group consists of 10 geological surveys under a co-operative framework. An effort to understand the tectonic development of the NE Atlantic region resulted in the formation of the NAG-TEC group. The NAG-TEC Tectonostratigraphic Atlas and ArcGIS database have been compiled and made available to the public. This book about the NE Atlantic Region comprises 17 published scientific papers based on the NAG-TEC project, or using results from the NAG-TEC compilation. The book is divided into sections, the first being an introduction to the NAG-TEC project.

The 17 papers are covered in the following sections, under these headings:

Stratigraphy
Geochronology and volcanism
Crustal structure
Focused studies
The oceanic domain and regional kinematics
The oil perspective

This is an interesting tome and is well illustrated with diagrams and maps. There is a reference section after each paper and an index to the whole book at the back. It is clearly written and full of information about the subject, some of which challenges earlier views, and anyone with an interest in this area would, I think, find something they would enjoy reading.

I will not pretend to have read each paper thoroughly, but I have skimmed through and concentrated on the sections of most interest to me. Some of the points that caught my attention are summarised below.

I was interested to read in the Introduction that earlier studies of the North East Atlantic helped to establish many of the key ideas driving the plate tectonic revolution, and the region is still at the centre of controversies regarding topics such as mantle convection, the origin and extent of mantle plumes and the process of plate break-up.

The second section, Stratigraphy, has only one paper — 'An overview of the Upper Palaeozoic — Mesozoic stratigraphy of the NE Atlantic Region'. This study has revealed constraints on the timing and nature of sedimentary basin development, which has implications for rifting and the break-up of Pangaea. It has also shown that there is no evidence for a continuous rift system along the proto-NE Atlantic until the Late Cretaceous.

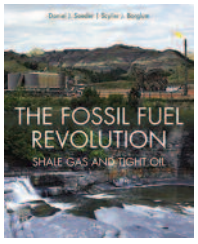
The following section deals with four papers under the heading 'Geochronology and Volcanism'. The first paper is a 'Compilation and appraisal of geochronological data from the North Atlantic Igneous Province (NAIP)'. Cenozoic igneous and volcanic rocks cover much of this province. The writers conclude that magmatism associated with the pre-rift phase started in the early Palaeocene (*c.* 64–63Ma) and continued into the Eocene *(c*. 56Ma). Episodes of post-rift volcanism carried on from *c.* 56–50Ma and intrusions are recorded up to 20Ma.

The second paper in this section is an overview of the distribution of volcanic facies over the North Atlantic region. New maps establish the pattern of volcanism associated with break-up and the initiation of sea-floor spreading. They suggest that a southward deflection of the Iceland mantle plume is a long-lived phenomenon, dating back to before the break-up of Pangea. The maps also show that emplacement of igneous crust on the margins is highly asymmetric, with the bulk of the new crust being emplaced closest to the thicker lithosphere associated with stable cratons.

This is an academic monograph with technical papers and is not written for the general reader, but it will be of interest to any student or researcher to the formation and continuing development of the North-East Atlantic Region.

— Anne Bunn

Book Review



Soeder, D., and Borglum, S. 2019 *The Fossil Fuel Revolution, Shale Gas and Tight Oil*. Elsevier (ISBN 978-0-128-15397-0; 354pp; paperback £115; also available in a Kindle edition £109.25)

As we look forward to the Glasgow Climate Summit (COP 26) in late 2020, the media make frequent reference to energy transitions and the reduction of our carbon footprint. This book describes the new energy resources obtained from shales and tight 'reservoirs'. Tight in this context usually applies to low porosity and/or permeability sandstones and carbonates, as well as to fine-grained clastics such as siltstones. These 'new' resources (the first ones) were first utilised in 1985 and have enabled the USA to overtake Saudi Arabia and Russia as a major oil and gas producer. The USA has become a net exporter of these products and no longer relies on imports from politically sensitive countries.

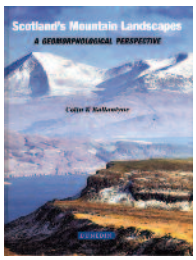
The book includes the development of horizontal drilling and hydraulic fracturing, which have enabled previously undrilled formations to become productive. Unfortunately, some of the chapters are a little dated and do not include the latest work on well spacing, well logging and environmental protection. Similarly, the work focusses on the original 10 shale gas targets and only includes a brief discussion of the main oil projects like those in the Permian Basin, the Bakken and the Eagle Ford, where most of the activity now takes place. Later chapters include work on environmental concerns and energy economics, and closes with a brief coverage of energy security and the politics of energy.

The target audience is quoted as industry members, undergraduate and graduate students, engineers and geoscientists. Soeder and Borklum have done a good job in covering the history of shale gas developments, but energy professionals will normally turn to recent industry and government reports rather than to this expensive volume.

— Tony Grindrod

Book review

Ballantyne, C.K. 2019 *Scotland's Mountain Landscapes: A Geomorphological Perspective*. Edinburgh: Dunedin Academic Press Ltd (ISBN 978-1-78046-079-6; 174pp; hardback £28.00)



"Nothing is static, nothing endures and nothing is eternal, even though within our brief individual lifetimes this may appear to be so." This quotation from page 138 summarises the overall theme of constant change that Colin Ballantyne so eloquently achieves throughout this book. Having enthused about geomorphology with my students throughout a career of teaching geography, I knew this was my kind of book and it did not disappoint!

This is much, much more than a book about Scotland's diverse mountains, it's staggering range of rock types of differing ages and the many processes operating here through deep time, many millions of years ago, through ice ages to today's weathering, erosion and deposition. The book as a whole tells a very coherent, detailed story of the development of the mountain landscapes we observe today and how these landscapes may look in the future. It is not a book of published scientific papers, equations and technical academic jargon, nor does the author shy away from all of those, but hits the middle ground, and the book is immensely readable and wonderfully illustrated.

The author, Colin Ballantyne, Emeritus Professor of Physical Geography at the University of St Andrews, with 40 years of glacial, peri- and post-glacial research experience working in a variety of global mountain environments has a wealth of ideas and material from which to draw for each chapter.

The introduction provides basic concepts and terminology for readers without prior knowledge, seating geology and geomorphology in time and space. The complex geological evolution of Scotland, no mean feat to comprehend, is systematically approached in Chapter 2 and usefully linked to five distinct, fault-bounded Scottish terranes, and the text refers to individual sites within these. Chapter 3 considers the influence of differing rock types on relief, but also highlights exceptions to the norm, for example, within the Hebridean terrane where Lewisian gneiss, Torridonian sandstone and Cambrian quartzite all underlie both mountains and low ground. The text is thought-provoking throughout; here, the reader is introduced to the idea that rock resistance to weathering and erosion is secondary to the combined role of landscape inheritance and patterns of Cenozoic tectonic activity, slope retreat and deep weathering.

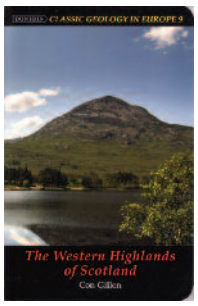
There follow two chapters that consider how successive episodes of glaciation have modified Scotland's mountain landscapes into their present forms. Specific glaciological terms, processes and landforms are dealt with in an easy style, aided by well-chosen photos, maps and diagrams. Catastrophic slope failure, in addition to lesser processes, are introduced in a further chapter with a stunning photograph of Beinn Alligin viewed across Lake Torridon where a large landslide scar can clearly be seen. I was pleased to see a chapter considering wind as a geomorphological agent, as these processes, as the author states, are often underestimated. The text highlights, among other topics, deflation surfaces on the northern plateau of An Teallach in Wester Ross, wind stripes in the Cairngorms and windblown sand deposits at the summit of The Storr (719m) on the Trotternish Peninsula on Skye. Anthropogenic influences are mentioned in places, especially our effect on the processes that are changing landforms at present.

I especially enjoyed reading the Key Sites chapter, sections of which could be followed as a kind of travelogue, that highlight specific areas to observe a range of processes and landforms, sometimes from roadside vantage points. There is a good 'further reading' section, specific to each chapter, but the author does not overload here. Rather, references are designed to provide readers with appropriate, comprehensible source material. There is an index to locations and an index of Scottish mountains and hills, as well as a comprehensive general index.

I found Colin Ballantyne's book to be very accessible and, although I read it cover to cover, it is also one to easily dip into. I recommend this book to anyone with an interest in mountains, from the walker and budding geologist through to those who study the mountains of Scotland.

— Sue Hughes, BSc (Hons) (Open), MA (Ed) (Open)

Book review



Gillen, Con 2019 *Classic Geology in Europe 9: The Western Highlands of Scotland.* Edinburgh: Dunedin (ISBN 978-1-78046-040-6; viii + 276pp; paperback £19.99; also ePub 978-1-78046-606-4 and Kindle 978-1-78046-607-1)

Dr Con Gillan's book *The Western Highlands of Scotland* is not a book for the timid geologist! This statement is not meant to put you off the book; quite the opposite. It is a field guide in the best sense of the genre. The book is another volume in Dunedin's growing series 'Classic Geology in Europe'. But just to be clear, we all know that Scotland isn't all 'European', but partly an ancient 'American' invasion, the result of the Caledonian Orogeny and the closing of the Iapetus Ocean through Ordovician times to early Devonian times some 390 million years ago.

This book is a field trip between round-cornered covers (so it gets less dog-eared taking it in and out of your rucksack). It covers the whole of western Scotland, excluding the Isles (inner and outer — planned as another volume in the series). The text is readable, but technical. It is structured like a field trip progressing in each regional trip locality by locality. The book is meant to be a carried guide, a set of notes, if you like, but more than that, for Dr Gillan directs you, points out what you should look for, explains what you see, explores, challenges and interprets the rocks, structures and formations.

An Introduction chapter explains the purpose of the book — as emphasised above — followed by a brief background to geological research in western Scotland, geological time and setting, and advice on route planning, safety when out in the field, sample collecting and maps. A more detailed Chapter 2 explains the 'Geological evolution of the Highlands'. Chapter 2 is an excellent summary of Scotland's geological evolution, worth reading just for that. It includes no fewer than six detailed tables summarising the geological history of main regions: the Lewisian Complex, the Torridonian rocks of north-west Scotland, the Cambrian to Ordovician Durness succession, the Moine rocks of Inverness-shire and Western Ross, the Dalradian in the western Central Highlands, and the geological timetable of north-west Scotland — all good exam review material!

The remaining seven chapters are field excursion regions, progressing systematically down Scotland's western half from north to south: 3 Tongue of Lochlinver, 4 Lochlinver to Assynt, 5 Ullapool to Gairloch and Loch Maree, 6 Gairloch to Kyle of Lochalsh, 7 Kyle of Lochalsh, Glenelg and Glen Roy, 8 Fort William, Glenfinnan, Lochailort, Ardnamurchan, Strontian, 9 Fort William to Easdale, Likmartin, Tayvallich and Kilmory, and finally 10 Ben Nevis, Glen Nevis, Ballachullish, Glencoe to Loch Lomond.

Each field trip chapter begins with an Introduction describing the general geology of the region and a detailed route map of the localities to be visited, including map references; then proceeds through the localities. These trips are generously illustrated with numerous colour photographs — altogether there are 143 good quality maps and photographs.

Dr Gillan ends his book by providing a nine-page section of references and suggested further reading, an excellent resource; plus a two-and-a-bit-page Appendix listing websites for seeking more geological detail about Scotland. Finally, a 19-page Glossary of geological terminology, a three-page list of relevant Gaelic terms one might encounter among the Highlands, and a 17-page Index.

This is definitely not a book to read and put down, but rather a book to have constantly in hand as you walk the Scottish Highlands. I truly wish I had this book available years ago when I tramped and climbed in many of the regions it so ably describes.

— Dr David M. Jones, OUGS Proceedings Editor

Book review

John, Brian 2018 *The Stonehenge Bluestones*. Greencroft Books (ISBN 978-0-90555-994-0; 256pp; paperback £15)

This is a book about where the bluestones at Stonehenge came from, written with feeling. It starts with the geology of Pembrokeshire, and then describes the bluestones at Stonehenge, describing the evidence for them and how many there are at Stonehenge. In 1921, Herbert Thomas proposed that the bluestones at Stonehenge had been transported there by people, as an aside in a talk about the origin of the bluestones. John then relates the various theories of bluestone transport, and modern recreations of the methods used, by land and by sea. One of these recreations included the 'Millennium stone', lost at sea but then retrieved, and involved an arduous journey on roads over which it took five weeks to pull the stone the first 17 miles.

John's next discussion is a diversion about Merlin and various myths and magical theories about Stonehenge.

In 2008 The Open University was involved in an excavation at the Preseli quarries, filmed as an episode in the BBC *Timewatch* series. The archaeologists suggested that the site could be the quarry from which the Stonehenge bluestones came. However, when geologists examined the stones, their faces and 'wedge' slots on them, they considered these marks to be natural rather than man-made.

The rest of the book concentrates on the stones and their geology. This includes the history of the stones, other examples of bluestones found near Stonehenge and glaciation. The author argues that the bluestones were transported on the Irish Sea glacier, south-east from Preseli towards Salisbury Plain, leaving a train of bluestone erratics scattered across the landscape. So, he claims, when the builders of Stonehenge needed stones, they simply collected the next nearest large ones. There are, in fact, several rock types in the bluestone circle at Stonehenge, including volcanic ash and Jurassic limestone, as well as bluestones. And as the glacier scatter had not left a sufficient number of bluestones, Stonehenge's builders used whatever suitable stones they could find. The monument was repeatedly reorganised and one theory is that it was never finished — there were never enough stones to finish it. When Herbert Thomas proposed the human transport theory, he was unaware of the extent of glaciation in south-west Britain, hence his suggestion that the bluestones had been brought by people from the Pembrokeshire to Stonehenge.

A good read, with much good geology. The story of the modern recreation of the human transportation theory is a story in itself, and an example of how a good story got in the way of the facts.

— John Lonergan, FGS, BSc (Hons) Geology (Open)

Book review

Lyle, Paul 2019 *Introducing Stratigraphy*. Edinburgh: Dunedin (ISBN 978-1-78046-022-2; ix +133pp; paperback £14.99; also as ePub 978-1-78046-559-3 and Kindle 978-1-78046-560-9)

Paul Lyle's *Introducing Stratigraphy* is another volume in Dunedin's growing series of 'Introducing' books. It is a slender book: subtracting blank verso pages and pages occupied solely by a figure there are only 110 pages of core text; and many pages are up to half occupied by a figure. Thus the information is basic, and this is indeed an entry-level book. I would recommend it to general readers and to senior school and sixth form students.

It has seven chapters: 1 Introduction: what is stratigraphy?; 2 The historical development of stratigraphy; 3 Time's Arrow and Time's Cycle: Uniformitarianism and Catastrophism in stratigraphy; 4 The quantification of the stratigraphic column: absolute time; 5 An integrated account of the stratigraphic column; 6 The definition of stratigraphic units and the Golden Spike; and 7 The application of stratigraphy. There is an untitled Epilogue, which is basically a less than one-age précis of the book's contents.

Like a student textbook key terms are identifiable as emboldened text; and there is a Glossary at the end of the book of these terms. Each glossary term has a number in square brackets but there is no explanation of what the number is — assuming that the reader will eventually realise that these are the paged numbers on which the term is first used. The final section is a one-page 'Further reading' list of 11 books and six inline resource links.

There is no index.

The book provides a basic level of introduction defining geological stratigraphy and chronology. It can be read in one sitting or two, after which I recommend that the reader move on to less basic books.

As a reviewer I must be honest and point out what I opine are some flaws and lack of attention to editing. Nearly two whole pages are occupied by a chronological chart called the 'Stratigraphic column' (Figs 2.15 and 4.9), with no explanation or reason for including both. The only differences between them are that the latter example is bigger, more brightly coloured, and has the dates of the geologic periods down one side. Other chronological charts in the book have different geological dates to those in Figure 4.9; and furthermore, the dates in Figure 4.9 differ from the dates of the International Chronostratigraphic Chart of Figure 6.1.

The captions to figures are almost all one line, and often give no information other than the place they depict. I found some citations to be to the wrong figure, and wonder if figure numbers had been changed or added to, and their text citations not rechecked. Some graphs show numerical values, but do not state what units they represent (time? distance?). There is inconsistency in the use of 'myr' and there are inconsistent spellings. There are cases where *Genus* and *species* names are not italicised. There are several stray numbers and colons in the text and a missed subscripted 'CO2'.

There is information stated in the core text, with a figure citation, and that information is missing in the figure, or differs in the figure. For example, the text citing Figure 5.8 declares that it shows northern hemisphere Pleistocene glaciation "viewed from directly above the North Pole" — the view actually appears to be from the Equator.

The text states that there is a "relatively stable sea level in the Ordovician", and cites an "end-Ordovician glaciation", but the red sea-level line in Fig 5.11 shows a pyramidal peak over the Ordovician time block and only has an arrow for a glaciation well to the right of even the beginning of the Ordovician division line on the graph, not even over the Ordovician time block.

The text's statement that there is a "a gradual fall [of sea level] through the Devonian, continuing through the Carboniferous" is not in agreement with the line showing a sea-level *rise* in the first half of the Carboniferous, a levelling off in the second half of the Carboniferous, and the a quite steep sea-level decline through the Permian. Further, Figure 5.11 curiously labels what must be the Silurian with the letter 'B'.

The palaeo-landmass, continental-migration maps through chapter 5 are interesting, and show a broad picture of the underlying plate tectonics and ocean openings and closings over time.

On page 67 the text states that, "during the Ordovician ... On land the earliest land plants began colonization." Then states on pages 67–68, "Following the mass extinctions at the end of the Ordovician, there was an expansion of life in Silurian ... and the first appearance of land plants." It is difficult, not to say confusing, for a reader to reconcile these statements.

Some sources of the figures cited in their captions are nowhere given in the sources list.

Figure 5.35 of five maps showing the breakup of Pangaea includes a map of the Jurassic Period that is missing the entire South American continent. It appears that the entire landmass sank below sea level between the Triassic and the Cretaceous!

Finally, page 85 states that that there are 100 stages in the Phanerozoic, but every time I count the stages in Figure 6.1 or in Table 6.1 I cannot make the numbers match.

It is difficult, not to say confusing, for a reader to reconcile these contradictory statements and apparent editorial errors.

— Dr David M. Jones, OUGS Proceedings Editor

Obituary

Margaret Wenban
7 February 1936 –15 December 2019

Many long-standing OUGS Members will remember Margaret Wenban, who was very active in the Society from about 1980 to about 2010. She was a teacher by profession, and some of her pupils at Kingston Road School in Staines still remember her with affection 30 or 40 years on. One said how much Margaret had enriched his schooldays with her kindness and warmth, not to mention the breadth of her knowledge.

Her home throughout most of her adult life was a house next to the polo ground in Windsor Great Park, where her husband, Dick, worked in the Valley Gardens. Their son Robin (born in 1958) and daughter Sarah (1960) had an adventurous childhood in the enormous 'garden' of the Great Park. OUGS Members also had some good times there, on a couple of occasions having to negotiate our way past the security surrounding a polo match to get to the house.

Both of Margaret's children showed talent and ability, with Robin obtaining a degree in geology and Sarah training to be a professional opera singer. All of their lives changed, however, when Robin died in 1979. It's nice to think of Margaret's own degree with the OU and her MSc from Kingston Polytechnic as a shared interest with Robin.

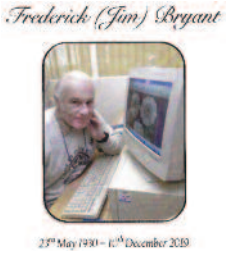
Margaret was a delight to be with. On OUGS trips, she occasionally came out with accidental puns, affectionately known as Margaretisms, that made us all laugh. On one memorable occasion she said gonads when she meant goniatites.

Apart from geology, Margaret had interests in many fields, particularly birdwatching and music. She travelled widely on geology and birdwatching trips, visiting every continent except Antarctica. Her local WI benefited enormously from this, as she gave frequent talks on where she'd been. She had a world map at the top of the stairs in her house with stars on all the places she'd visited — it was very impressive.

Sadly, her travels largely came to an end when she was diagnosed with Alzheimer's. She continued to live at home until she lost her mobility and had to move into a care home. With help, she managed to walk into Dormy House in Sunningdale on 8 August 2018 and never really walked again. She died peacefully on 15 December 2019. Tributes at her funeral showed how much she was loved by everyone who knew her. She is survived by her daughter Sarah, three grandsons, and her brother and sister and their children.

— Barbara Cumbers, OUGS London Branch

Obituary



Frederick (Jim) Bryant
23 May 1930–10 December 2019

Jim Bryant, a long-standing OUGS Member, sadly passed away in December. Many Members will remember his enthusiasm for geology and palaeontology — he spent vast amounts of time travelling the world collecting fossils to add to his huge collection. He would take the more unusual specimens to The Natural History Museum in South Kensington for identification, eventually donating them to various National Collections. In 2006 he was awarded the Geological Society's R. H. Worth prize for his outstanding contribution to the furtherment of amateur geology. Jim was a member of many national and regional geological and palaeontological societies, usually helping to run them, culminating in his post as Chairman of the Tertiary Research Group for more than two decades. His inspiration to both old and young provides an enduring legacy to his long and active life.

— Dr Helen Craggs, OUGS London Branch (formerly Oxford Branch)

Obituary

Charles Philip Gordon Clark
1956–2018

The OUGS has been notified of the death of Philip Clark (he was Charles Philip Gordon Clark and went by Philip in OU/OUGS circles). Philip was in OUGS Severnside Branch. This is the obituary from the Worcester College (Oxford) website.

"10 July 2018 Charles Gordon Clark (1956) has died, aged 82. Charles read History together with John Holroyd (d 2014); they remained the greatest of friends throughout their lives. John was godfather to Charles's daughter Sophie, and John named his son Stephen Charles. Sophie and Stephen married in 2004, bringing the two families together for another generation and more.

Charles was ordained as a priest after leaving Oxford, and after his marriage to Thalia Oldham, ministered in Haslemere (Surrey), as Chaplain at Tonbridge School, thence Keston (Kent) and finally Tunbridge Wells, before leaving the ministry to retrain and work as a drystone waller in mid-Wales, being active in setting up and running the South Wales branch of the Dry Stone Walling Association. This work inspired in Charles a fascination with stone in the landscape, and in geology in general, which led him to an Open University degree in Earth Sciences and geologising/drystone walling trips all over the world. Charles sustained an active interest in the OU Geological Society. In later years he returned to his historical research interests, with years of research into family history and, latterly, in local history as a prominent member of the Bromyard History Society following his move with Thalia from Powys to Herefordshire.

Charles is survived by his wife Thalia, daughter Sophie, son Alexander, and four grandchildren."

— from Anne Burgess, Scotland Branch

Obituary

Rosalie Grainger
1946–2016

Rosalie died suddenly on 1st November 2016.

She was a good friend of mine and to many others. She was very clever, with a BSc and also an MSc. She studied with the Open University and also at Queens University Belfast.

Rosalie helped me on many occasions with field trips, particularly in Co. Antrim. She had extensive knowledge of the area. Only a few months before she passed away she helped with our Branch field trip to Islandmagee. She showed me a quarry in Whitehead, which I never knew existed even though I have travelled to Whitehead many times since I was a child. She showed us her extensive knowledge of fossils in Islandmagee. Her participation on the trip was greatly appreciated.

She had many interests. She belonged to our OUGS Ireland Branch and to the Belfast Geologists Society, where she was a past Chairperson and had also been Treasurer. She belonged to the Belfast Field Club and this gave her an extensive knowledge of plants and flowers.

Rosalie gave her time willingly, not least to her church, St. Patrick's Parish, Ballymena, where she was a Church Warden. She helped here with the services and many other events in the church.

Rosalie will be greatly missed by her husband David and three children Paul, Karen and Mark.

We will miss you too Rosalie.

— Phyllis Turkington (Ireland Branch Organiser)

Editor's notes to contributors

Following are guidelines for the submission of articles to the *Proceedings of the OUGS*. The principal theme encompassed within these guidelines is 'please keep it simple'. Let your editor do his job and please do not try to simulate, emulate or reproduce the page layout of the *Proceedings*. I have dedicated page-layout software (QuarkXPress) to do this and any special formatting, special characters and embedded illustrations that you include in a word-processing document can be lost (at best) or seriously confuse and crash (at worst) my iMac or the QuarkXPress software when I import it into the layout.

If your article contains special characters (such as mathematical symbols), please draw these to my attention — I will probably spot them anyway — so that I can import them properly with the glyphs menu in QuarkXPress.

Here are the basic guidelines. I will contact you about any queries that arise when I read your article. I will send you an edited version, showing you any changes that I have made and raising any queries or requesting any missing information.

Guidelines for *OUGS Proceedings* articles

As *OUGS Proceedings* Editor I do not want the publication of your article to be more work than is necessary for you (or for me!). Your article need not be more than about 1,500 to 4,000 words in general, but I leave the length up to you to suit the material you are writing about.

Regarding articles from the presenters of lectures at the OUGS AGM and Symposium, all OUGS members are grateful to you for presenting a lecture to us on your research, and for agreeing to submit a version of your talk for publication in the *Proceedings*. The purpose of this is to make your information available to OUGS members and others who could not attend the Symposium. As OU students and OUGS members we enjoy hearing and learning the information these events bring to us.

All that is necessary are:

• A Word (or compatible) file of the text: There is no need for you to attempt to format the text in any way using tools in Word or other word-processing software. I will do the page layout format in the *Proceedings* house style, using dedicated publication-industry-standard page-layout software (QuarkXPress). However, feel free, if you wish, to use **bold** and/or *italics* to indicate headings and subheadings so that I can identify and set these into house style.

I do not require a hard copy, but if you need to point out special characters or attributes in your article, it may be a good idea to send one with these items marked up or otherwise highlighted. I can accept electronic files attached to e-mails, text and image files on a CD or on a flash drive, or via shared media.

• Each illustration, chart, graph, map or other illustration as a separate digital file in high resolution: 300dpi minimum for colour or half-tone images; as high a dpi as possible, please, for line illustrations. Tables composed in Word or Excel are fine, as they are just text. A rough guide to the number of figures in an article is 10 to 30. Obviously as an AGM or Symposium presentation speaker you might have shown numerous slides, so please use your best judgement on the number to publish with your article — again, usually 10 to 30 is only a rough guide.

• Please be sure that we have permission to publish any illustrations that are not yours: Also, please give me the appropriate information to cite in acknowledgement in the figure caption; and please tell me in writing or in an e-mail message that you have obtained the permission necessary for each illustration in your article that is not yours.
As the author, this responsibility is yours.

• Please do *not* embed your illustrations in Word picture boxes within the text: All that is necessary is to indicate, by a reference within ( ) or within [ ] in your text, where the illustrations should go.

• You can submit the material as attachments to e-mails to me or send it to me on a CD or flash drive: I am on BT Broadband, so I can receive large files. It is usually best to attach only a few illustration files each to several e-mails. This applies especially to large files of photographs, charts and graphs. Alternatively, a digital sharing package can be used, such as Dropbox or similar.

• Where appropriate, cite your sources, or make it clear that a statement is a supposition, or solely your own view or opinion. We use Harvard style citations in the text: (author date, pages), e.g. (Jones 2004, 51–3); and your sources or references should be listed in alphabetical order by author and date at the end of your article. You need to list the author, date of publication (or of access to a website), full title, periodical volume or number, or place of publication and publisher, and page numbers.

If you miss out anything, I will ask you for it.

If your list includes items not cited in your text, it will be called 'Sources'; if all items in your list have been cited in your text, it will be called 'References'.

That really is it! The editing and page layout are my job, so let me do it for you. I will communicate with you as necessary as I do this, with queries or difficulties with any formats, special symbols, characters, etc, as is the task of any editor.

For you really keen authors, regarding grammar and spelling I use:

Butcher, J. 1992 *Copy-Editing: The Cambridge Handbook for Editors, Authors and Publishers* (3rd edn). Cambridge: Cambridge UP

The Oxford English Dictionary

The Penguin Spelling Dictionary 1990. London: Penguin Books Ltd

Ritter, R. M. (ed and comp.) 2000 *The Oxford Dictionary for Writers and Editors* (2nd edn). Oxford: Oxford UP

Ritter, R. M. (ed and comp.) 2002 *The Oxford Manual of Style*. Oxford: Oxford UP

Please feel free to contact me at any time about your article:

Dr David M. Jones, *OUGS Proceedings* Editor, 41 Blackburn Way, Godalming, Surrey GU7 1JY; 01483 424308;
proceedings@ougs.org

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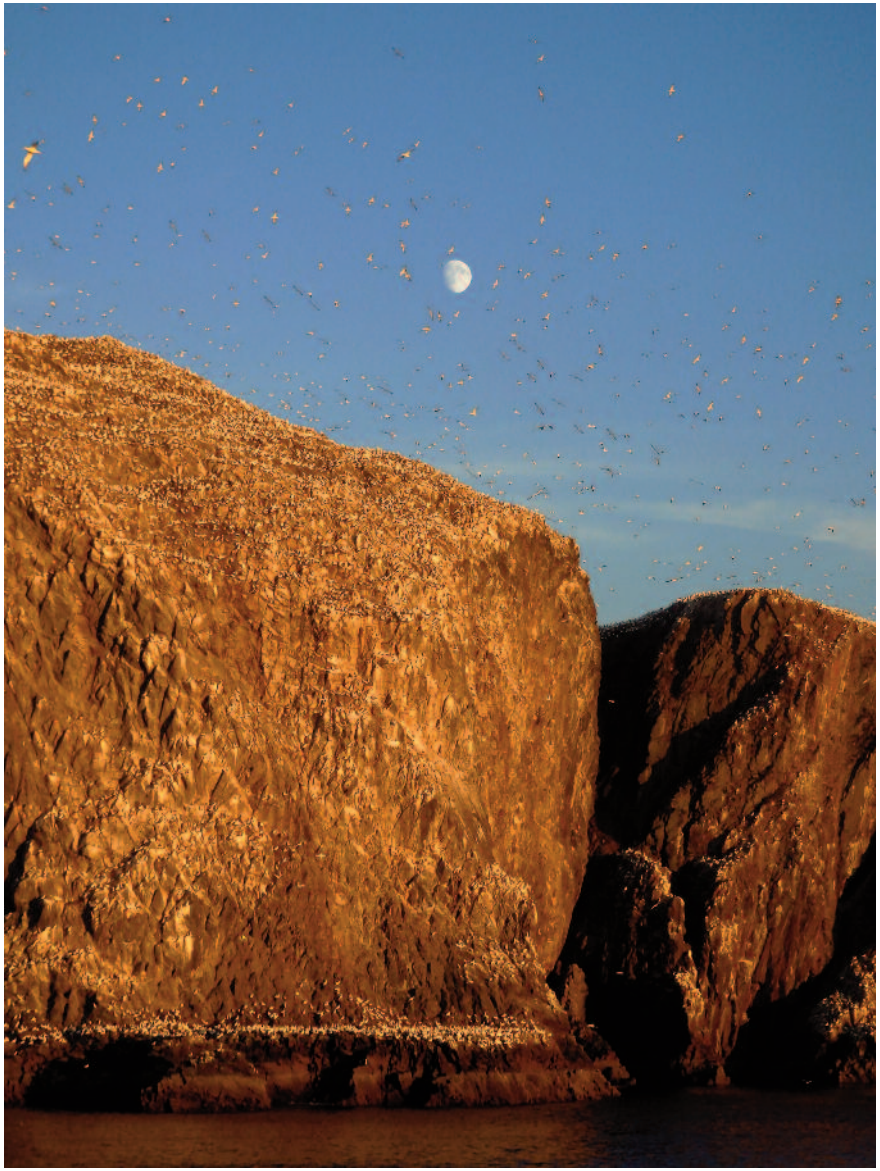
OUGS Moyra Eldridge Photographic Competition 2019

Winning and Highly Commended photographs

Geologically inspired landscape, structure or feature in the British Isles, Winner — Philip Findlay
Silurian ripple marks in the cliff at Marloes Sands

Silurian ripple marks exposed in several places in the Coralliferous Group beds (*c.* 430Ma) in the cliff at Marloes Sands, Pembrokeshire. The bright colours of a fresh exposure of ripple marks, almost in the middle of the picture, contrast strongly with duller, weathered exposures such as those near the picture's left edge.

Geologically inspired landscape, structure or feature, British Isles, Highly Commended — Kath Addison-Scott
Langport Member, Lavernock, Penarth, Wales
Langport Member of the Lilstock Formation, cliffs at Lavernock near, Penarth, Wales. This was the site of the 'Welsh Dragon' find *Dracoraptor hanigani*.



Geologically inspired landscape, structure or feature, British Isles, Highly Commended — Jenny Forrest
Bass Rock, Firth of Forth: Sunset, Moon Rise and Gannets
Bass Rock in the Firth of Forth stands 107m high. It is a volcanic plug of Carboniferous age and is of phonolytic trachyte composition. The photograph was taken of the north-west side of the rock as the Sun was setting. It is a Site of Special Scientific Interest, home to a colony of more than 150,000 gannets for most of the year.

Geologically inspired landscape, structure or feature anywhere else in the world, Winner — Peter Bratt
also, OUGS Popular Vote Winner
Cavernas de Mármol, General Carrera Lake, Patagonia, Chile

The Marble Caves (Cavernas de Mármol) at General Carrera Lake, Patagonia formed within cliffs of highly folded marble >100m high. They have been eroded at the base by the blue waters (rock flower) of General Carrera Lake, which was formed *c.* 6,500 years ago by melting glaciers.

Geologically inspired landscape, structure or feature elsewhere in the world, Highly Commended — Geoff Downer
"No vestige of a beginning, no prospect of an end", Monument Valley, Utah

The quotation from James Hutton's *Theory of the Earth* (1785) sums up the concept of Deep Time. Here at Monument Valley we see the Permian rocks of the Organ Rock Shale overlain by the massive and cross-stratified de Chelly Sandstone that forms the upstanding monuments' soft shales of the Cutler Formation form the valley floor. Monument Valley is a Navajo Tribal Park in the Navajo Nation, the largest land area retained by a Native American tribe and sometimes described as a 'nation within a nation'. The Navajo people have occupied these lands for more than 600 years.

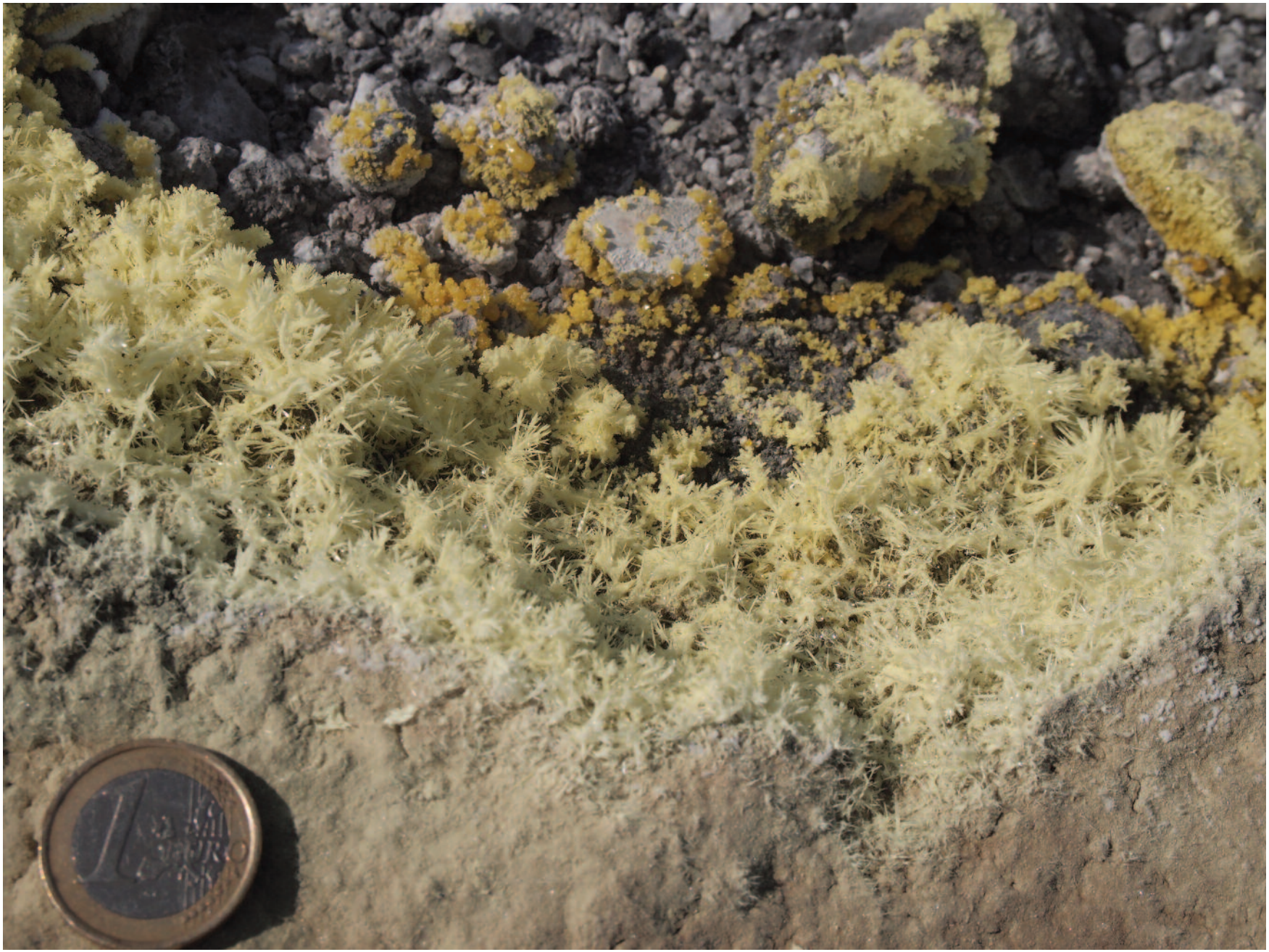
Industrial geology, Winner — Linda Fowler

Fros y fran open-cast coal mine near Merthyr, South Wales

A large open cast pit in the South Wales coalfield near Merthyr, now the subject of ongoing battles about who pays for restoration.

Industrial geology, Highly Commended — Peter Bratt
Salt mine, high Atacama Desert, Chile
This salt 'mine' in the high Atacama Desert, exploiting a desert deposit some 5km across, was worked (by pickaxe and shovel) until the 1970s when it became uneconomic compared with solar evaporation of seawater. The face is *c.* 5m high.

Mineral, rock or fossil specimen, or thin section/SEM view, Highly Commended — Linda McArdell
Fossil Sale, Tangier
Find the Fossil.



Mineral, rock or fossil specimen, or thin section/SEM view, Winner — Kath Addison-Scott

Sulphur crystals

Sulphur crystals deposited at fumaroles on Vulcano, Sicily. These sulphur crystals were deposited on the edges of fumaroles on the slopes of Vulcano. This is a volcano on the island of Vulcano, Sicily.